Local Area Augmentation System Performance Analysis Report

Report #2

Reporting Period: April 1 to June 30, 2004

Federal Aviation Administration
William J. Hughes Technical Center
Solution Development Division
LAAS T&E Team
Atlantic City International Airport, NJ 08405

Executive Summary

The Solution Development Division of the Federal Aviation Administration's (FAA) William J. Hughes Technical Center, Local Area Augmentation System (LAAS) Test and Evaluation (T&E) Team, provides this LAAS Performance Analysis Report (LPAR). This quarterly report is the second such document, and for this reporting period utilizes the FAA's LAAS Test Prototype (LTP) #1[1] as the subject LAAS Ground Facility (LGF).

LTP #1 a government-owned suite of equipment located on the Air Operations Area (AOA) of the FAA William J Hughes Technical Center at the Atlantic City International Airport (ACY). The LTP is completely operational and is utilized for flight-testing, in addition to data collection utilized in this report. The LTP has been in successful operation, and gathering valuable data, since 1997.

The LTP is the FAA's primary LAAS Research and Development (R&D) tool and is used to characterize and test performance of a typical LAAS installation in an operational airport environment. The LTP was designed with testing in mind, and its testing legacy continues to this day. As an FAA test system, the LTP is utilized in limited modified configurations for various test and evaluation activities. This system is capable of excluding any single non-standard reference station configuration from the position solution. The performance reporting of the system is represented only from LAAS standard operating configurations, meaning that non-standard configurations are excluded from the statistics for any portion of the reporting period, unless otherwise specified. Special configurations and maintenance details are included in a separate section within this report.

Table 1 summarizes observations of the major performance parameters used as a representation of accuracy and integrity for this reporting period. All units are in meters.

Parameter	Maximum Observation	Minimum Observation
Vertical Protection Level (VPL)	3.8	1.441
Horizontal Protection Level (HPL)	2.322	1.165
Clock Error	18.938	2.023
Dilution of Precision (DOP) (VDOP) (HDOP)	 2.59 1.609	 0.9 0.731

Table 1: Key Performance Summary

[1] LTP #2 is deployed in Rio De Janeiro, Brazil where Government LAAS flight-testing is being conducted, while critical ionospheric ground data is being collected. The LAAS T&E team is responsible for the analysis of all data gathered from the remote system.

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1. Introduction

The FAA is actively involved in the development of LAAS performance requirements and architecture, and has maintained a LAAS Test Prototype (LTP) to evaluate new concepts and resulting performance benefits. The LAAS T&E team utilizes a number of tools and methods to analyze system performance. These tools include a raw data analysis technique known as Code Minus Carrier (CMC), to closely observe errors down to a single Satellite Vehicle (SV) on a single Reference Receiver (RR). Additional system level techniques are mature enough to display key system performance parameters in real time. The LAAS T&E team has adapted the LAAS software to actively gather these key parameters for the data plots to be presented in this report.

Objectives of this report are:

a) To briefly introduce LAAS concepts and benefits.
b) To provide a LTP (LAAS) system level overview to aid in comprehension for persons unfamiliar with the material.
c) To present Global Positioning System (GPS) constellation, and SV availability at ACY, and any unfavorable bearing on overall system performance.
d) To briefly document LTP testing and maintenance activities.
e) To present the LAAS system's ability to augment GPS by characterizing key performance parameters.
f) To provide a key performance summary and full performance plots.

2. Aerial Photograph of LTP at ACY with Overlay

Figure 1 is an aerial shot of the FAA's LTP taken during a LAAS flight test. This valuable FAA R&D tool provides a valid representation an actual LAAS installation in an operational airport environment. The major system sites are identified.

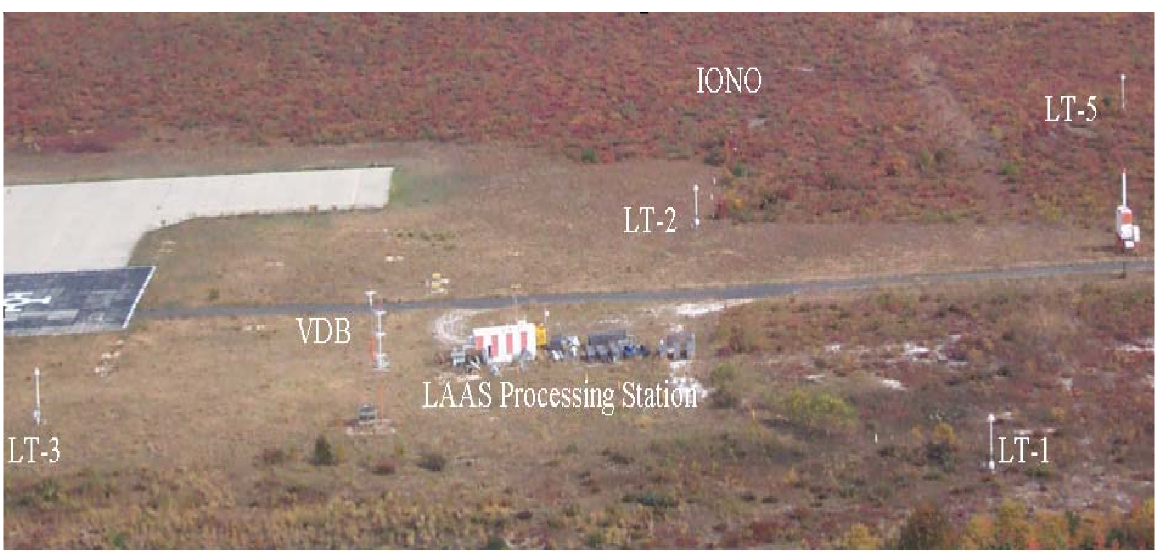


Figure 1: Aerial of LTP at ACY

3. LAAS Overview

This section is provided for persons unfamiliar with LAAS concepts and components. This brief overview is intended solely as an introduction.

A LAAS is essentially an area navigation system with its primary function being a precision landing system. The LAAS provides this capability by augmenting the Global Positioning System (GPS) with differential corrections.

3.1 LAAS Operational Overview

A Local Area Augmentation System (LAAS) ground facility (LGF) includes four Reference Receivers (RR), four RR antenna (RRA) pairs, a Very High Frequency (VHF) Data Broadcast (VDB) Transmitter Unit (VTU) feeding an Elliptically Polarized VDB antenna. These sets of equipment are installed on the airport property where LAAS is intended to provide service. The LGF receives, decodes, and monitors GPS satellite pseudorange information and produces pseudorange correction (PRC) messages. To compute corrections, the ground facility compares each pseudorange measurement to the range measurement based on the survey location of the given RRA.

Once the corrections are computed, integrity checks are performed on the generated correction messages to ensure that the messages will not produce misleading information for the users. This correction message, along with required integrity parameters and approach path information, is then sent to the airborne LAAS user(s) using the VDB from the ground-based transmitter. The integrity checks and broadcast parameters are based on the LGF Specification, FAA-E-2937A, and RTCA DO-253A (Airborne LAAS Minimum Aviation Performance Standards or MOPS).

Airborne LAAS users receive this data broadcast from the LGF and use the information to assess the accuracy and integrity of the messages, and then compute accurate Position, Velocity, and Time (PVT) information using the same data. This PVT is utilized for the area navigation (RNAV) guidance and for generating instrument landing system (ILS)-look-alike indications to aid the aircraft on an approach. A developmental airborne system that is capable of this type of navigation is referred to as a Multi-Mode Receiver (MMR). The MMR coupled with a LAAS can generate mathematical paths in space to any number of waypoints and touchdown points in the local area.

One key benefit of the LAAS, in contrast to traditional terrestrial navigation and landing systems (i.e. ILS, MLS, TLS, etc.), is that a single LAAS system can provide precision guidance to multiple runway ends, and users, simultaneously. Only the local RF environment limits this multiple runway capability. Where RF blockages exist Auxiliary VDB Units (AVU) and antennas can be added to provide service to the additional runways. This capability can also be built upon to provide service to adjacent airports.

3.2 LAAS Simplified Block Diagram

Figure 2 is provided as an illustration of LAAS operation with major subsystems, ranging sources, and theoretical user (MMR) identified.

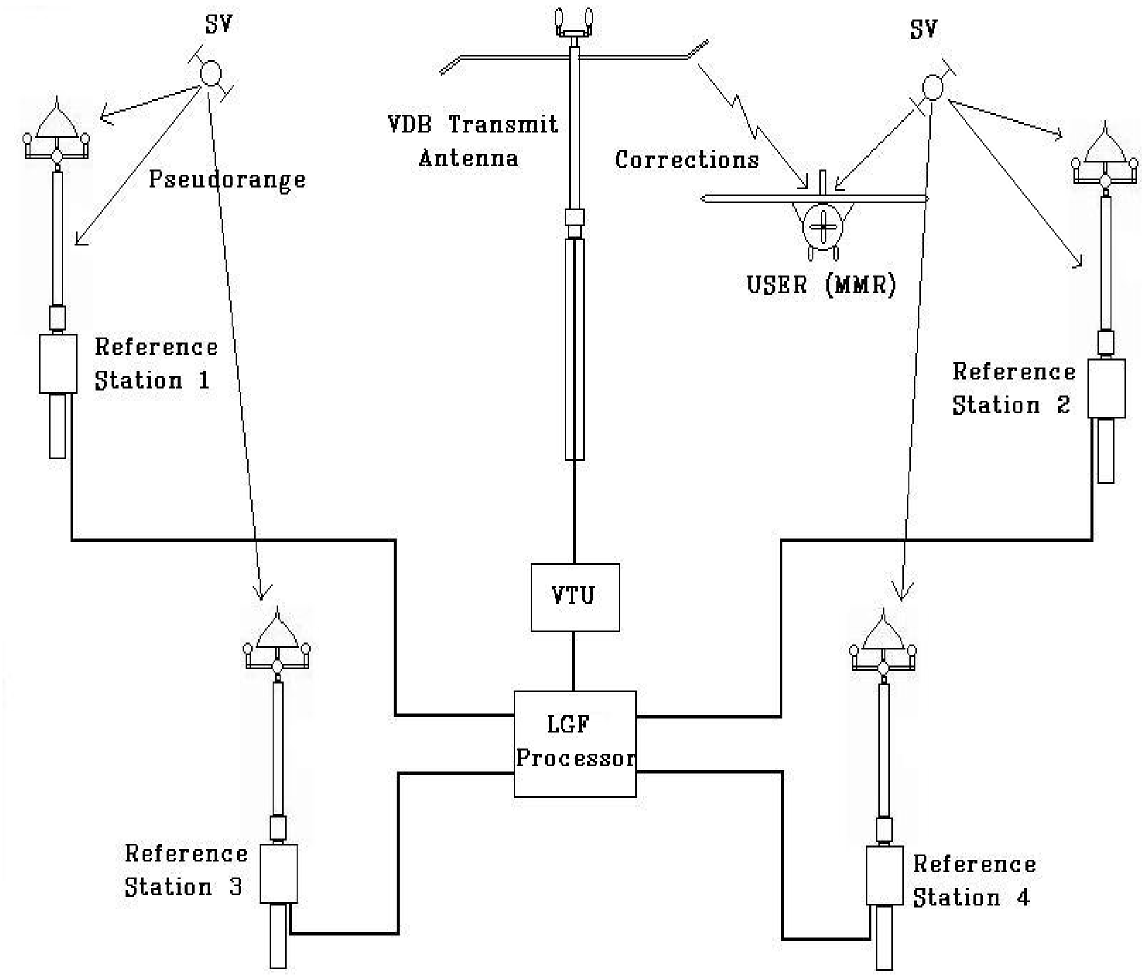


Figure 2: LAAS Simplified Block Diagram

4. GPS Constellation from ACY

Satellite Vehicle (SV) availability and constellation geometry has an impact on overall LAAS system performance. This section provides a snapshot of the expected constellation for the reporting period. GPS Notice Advisory to Navstar Users (NANUs) are known SV outages events that are excluded from these plots, but are included at the end of this section.

4.1 SV Availability Plot

ACY has a fairly robust available constellation expected throughout most of the sidereal day with four periods where the observable SVs are forecasted to drop below eight.

Figure 3 is an SV availability prediction graph representative of the reporting period. The graph does not account for any NANUs following the generation of the plot. It also does not include the WAAS geo-stationary satellite.

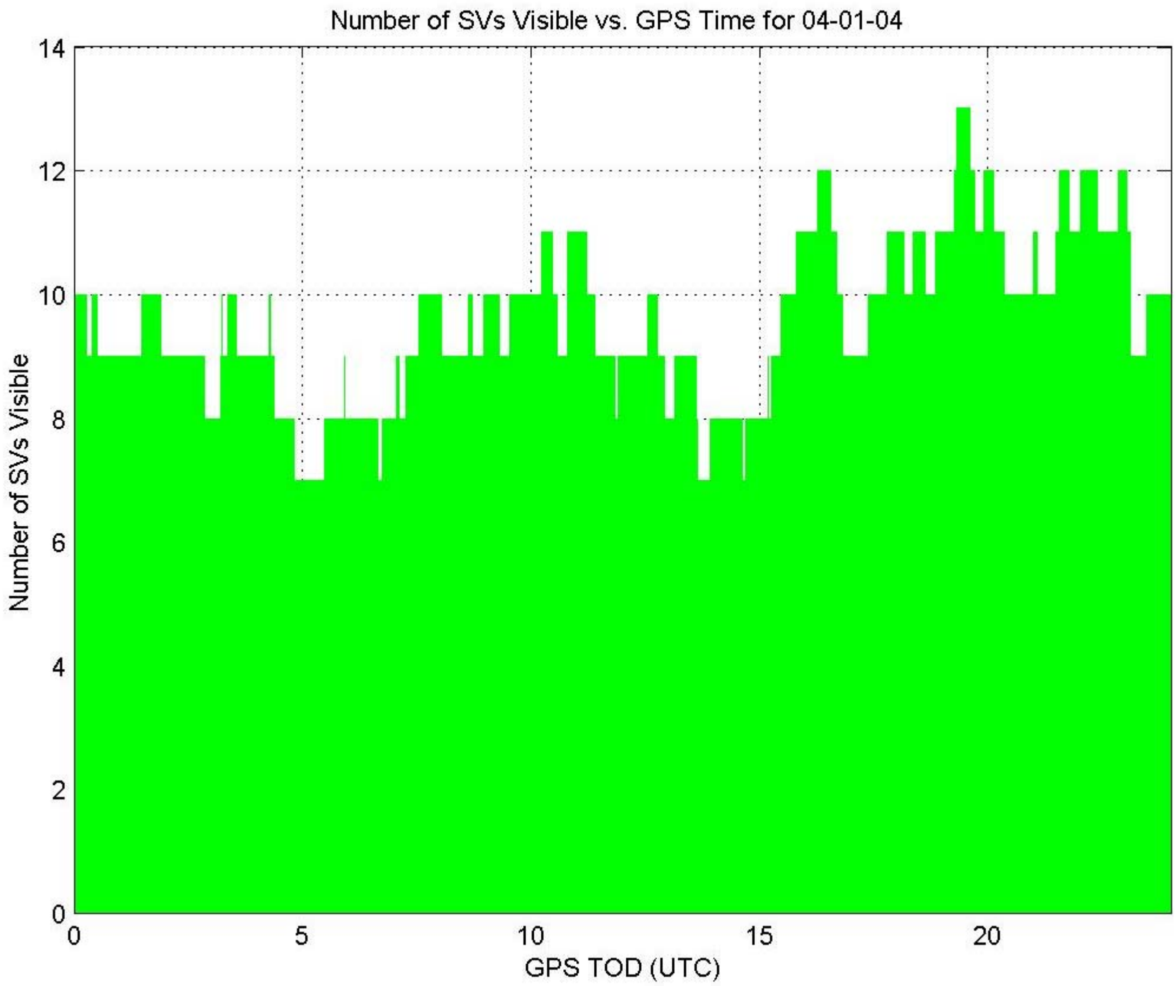


Figure 3: SV Availability at ACY

4.2 SV Elevation Plot

SV elevation and the resulting geometry have a bearing on the overall LAAS performance. The LAAS reference station antennas are of a dual segment design and are referred to as the Integrated Multi-Path Limiting Antenna (IMLA). The two segments (upper and lower) have patterns that overlap each other centered at approximately 29 degrees elevation with an overlap of about 13 degrees above and below this point. At least one common SV must be tracked by the two segments in order for the LAAS software to calculate the hardware bias inherent in such systems. The more common satellites tracked, the better the estimation of the hardware bias. The elevation of the

Wide Area Augmentation System (WAAS) geo-stationary satellite from ACY is approximately 39 degrees, and can serve as a steady ranging source available for the bias calculation.

Figure 4 is an SV elevation prediction graph representative of the reporting period. The graph does not account for any NANUs following the generation of the plot.

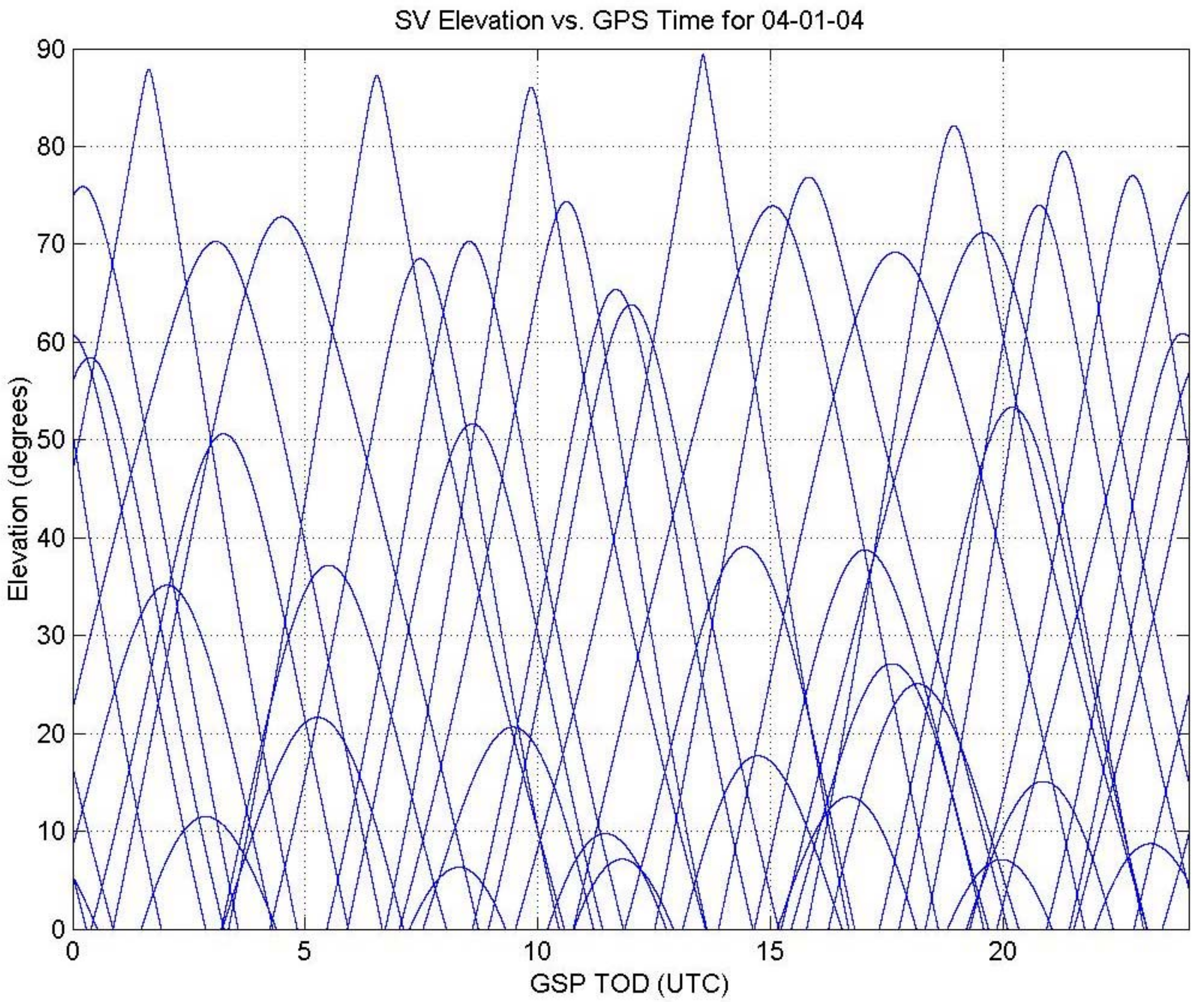


Figure 4: SV Elevations at ACY

4.3 Notice Advisory to Navstar Users (NANUs)

The GPS constellation is designed to provide adequate coverage for the continental United States for the majority of the sidereal day. A NANU is a forecasted or reported (un-forecasted) event of GPS SV outages, and may cause concern if the SV outage(s) affects minimum required SV availability or causes a period of no common satellites in the overlap region of the IMLA antenna.

NANUs that caused an interruption in service (where Alert Limits are exceeded) will be highlighted within NANU summary Table 2. Although such an interruption is unlikely, the LAAS T&E team closely tracks the NANUs in the event that post-data processing reveals a rise in key performance parameters. Any highlighted NANUs will include additional data plots (section 8.4), and accompanying narrative in the "Performance Summary" section (8.3).

The NANUs provided include only definitive SV outages. An "Outage Summary" provides the actual period of the forecasted SV outage. An "Unusable" provides the same information for an un-forecasted SV outage. An occasional "Usable" will be seen for SVs that were "Unusable" from the previous reporting period. An "Unusable UFN" is an SV outage that remained unusable beyond the end of the reporting period. Table 2 provides actual SV outages for the reporting period.

NANU #	NANU Type	PRN	Date Begin	UTC Begin	Date End	UTC Ended
2004041	Outage Summary	PRN-30	04/01/04	1341	04/01/04	1703
2004043	Usable	PRN-19	04/05/04	1706	N/A	N/A
2004045	Outage Summary	PRN-03	04/07/04	1810	04/07/04	2137
2004047	Unusable	PRN-04	04/11/04	1511	04/11/04	1629
2004048	Outage Summary	PRN-06	04/13/04	0907	04/13/04	1818
2004050	Outage Summary	PRN-08	04/22/04	1338	04/22/04	1650
2004053	Unusable	PRN-08	05/03/04	1117	05/05/04	0503
2004055	Outage Summary	PRN-31	05/04/04	1828	05/05/04	1058
2004056	Unusable	PRN-02	02/22/04	1037	05/12/04	1701
2004057	Decommission SV	PRN-02	05/12/04	1701	N/A	N/A
2004063	Outage Summary	PRN-16	05/20/04	2345	05/21/04	1145
2004064	Unusable	PRN-08	05/05/04	0906	05/18/04	0142
2004065	Outage Summary	PRN-17	05/19/04	1703	05/19/04	2205
2004068	Outage Summary	PRN-16	05/21/04	0028	05/21/04	0657
2004069	Outage Summary	PRN-06	05/25/04	1149	05/25/04	1413
2004070	Outage Summary	PRN-22	05/27/04	1722	05/28/04	0059
2004072	Outage Summary	PRN-29	06/17/04	1241	06/17/04	1639
2004077	Outage Summary	PRN-07	06/25/04	0403	06/25/04	1238
2004079	Outage Summary	PRN-01	06/28/04	2342	06/29/04	0958

Table 2: NANU Summary

5. Configuration

This section provides a description of the LTP system configuration in terms of hardware and software for the reporting period. Since the LTP is the FAA's primary R&D tool for LAAS these sections may vary somewhat between reporting periods. The majority of these changes will likely first emerge in Section 5.4.

5.1 Master Station

The LTP Master Station or Processing Station is a complex collection of hardware and related interfaces driven by a custom software program. The master station hardware and software operations are described in this section.

5.1.1 Master Station Hardware

The Master Station (or processing station) consists of an industrialized Central Processing Unit (CPU) configured with a Unix type real time operating system. The CPU is configured with a SCSI I/O card for mounting an external hard drive. This hard drive collects all raw reference station GPS data messages in parallel to the processing of those messages. The drive is also used to collect debugging files and special ASCII files utilized to generate the plots found in this report. These collected files are used for component and system level performance and simulation post processing.

The CPU is also configured with a multi-port RS-232 serial card to communicate in real time with the four reference stations and to the VDB. The reference stations continuously output raw GPS messages to the CPU at a frequency of 2 Hz. Data to and from the reference station fiber lines is run through media converters (fiber to/from copper), which provides a RS-232 serial signal to the CPU's multi-port serial card. The CPU then generates the LAAS corrections and integrity information and outputs them to the VDB.

The VDB Transmitter Unit (VTU) is capable of output of 150 watts and employs a TDMA output structure that allows for the addition of auxiliary VDBs (up to three additional) on the same frequency for coverage to terrestrially blocked areas. The LTP's VTU is tuned to 112.15 MHz and its output is run through a band pass, and then through two cascaded tuned can filters. The filtered output is then fed to an elliptically polarized three bay VHF antenna capable of reliably broadcasting correction data the required 23 nautical miles.

Surge and back-up power protection is present on all active master station components.

5.1.2 Master Station Software

Ohio University (OU) originally developed the LAAS code through a FAA research grant. Once the code reached a minimum of maturity, OU tested and then furnished the code to the FAA (circa 1996). It was developed using the C programming language under the QNX operating system. QNX was chosen because of its high reliability and real-time processing capability. This LTP code has been maintained by the LAAS T&E team since that time and has undergone numerous updates to incorporate evolving requirements and hardware. The current internal Revision Control System (RCS) version is 1.25.

The code stores the precise survey data of the four LAAS reference station antennas (all eight RRA segments). The data structures are initialized, input files are opened, and the output files are created. Messages are received via four serial RS-232 connections, which are connected to four GPS receivers. The program cycles through the serial buffers and checks for messages, if one is found it gets passed to a decoding function. From there it is parsed out to functions according to message type and the information from the messages will be extracted into local LTP variables. Once the system has received sufficient messages the satellite positions are calculated in relation to the individual reference receivers. Next the system corrects the phase center measurements for the stacked dipole antenna array and converts the measurements from the individual reference locations to one simple reference location. The High Zenith Antenna (HZA) and dipole measurements are then combined to form one virtual reference receiver at the reference location. Then the integrity and protection equations are processed which produces the alert levels for the LGF. Next the position solution and reference position is calculated. Messages are then encoded and sent to the VDB via a RS-232 connection. Each of the three message types are encoded separately and sent according to DO-246B standards. The final step in the LGF software is to update the graphics and respond to the user inputs. At this point the software checks for problems that may have occurred during the processing and will either stop the program, or restart the cycle by reading the serial data.

5.2 Reference Stations

There are four reference stations included in the FAA's LTP as required in the LAAS specification. The LTP's reference stations are identified as LAAS Test (LT) sites; there were originally five LT sites (1 through 5) but #4 was abandoned in favor of the remaining four LT sites (see Figure 1).

Each reference station consists of 2 major component systems. The first is a hybrid GPS antenna system referred to as an IMLA. The second is the reference receiver and transmit system.

5.2.1 The Integrated Multipath Limiting Antenna (IMLA), and the Multipath Phenomenon

The IMLA (see Figure 5) is a hybrid, two receiving segment, GPS antenna that is approximately 12 feet in height and 100 pounds in weight. The two segments (top and bottom) have specially designed overlapping patterns and high Multipath rejection.

Figure 5: The IMLA Antenna

Multipath is a phenomenon, which is common to all Radio Frequency (RF) signals, and is a particular concern in differential GPS navigation (i.e., LAAS). The two major types are Reflected and Diffracted Multipath. Diffracted Multipath is the bending of a signal around the edges and corners of structures and other obstructions. Reflected Multipath is the bouncing of the signal on any number of objects including the local water table. Signals that bounce off the water table is referred to as Ground-Bounce Multipath. In all cases the path length is increased. This path length is critical in GPS since the ranging is based on signal's Time of Arrival (TOA). Multipath can cause a standard GPS system to track an indirect signal rather than the direct GPS signal. This causes a pseudorange error, for the SV being miss-tracked, in the amount of the indirect signal's additional path length. This pseudorange error will translate directly in to the position solution.

Siting criteria developed around the IMLA antenna mitigates the diffracted and above ground level Reflected Multipath. The IMLA pattern design serves to mitigate the Ground-Bounce Multipath.

The bottom segment, the most critical component of the IMLA, is a 14-element stacked dipole array, which is used to include SV measurements from 5 to 40 degrees in elevation. Signals from low elevation satellites are generally lower in power and more susceptible to ground bounce Multipath, which enter conventional GPS antennas from below 0 degrees. The measurement error caused by the Multipath reflection is proportional to the ratio of the signal strength of the desired direct signal path to the strength of the undesired reflected path. The stacked dipole array is designed with a high gain lobe in the direction extending from 5 to 30 degrees, and is reduced by 35 dB at –5 degrees, providing a strong desired to undesired ratio. The result is a limit on pseudorange measurement errors on the order of 0.3 meters.

The top segment, referred to as a Multipath Limiting High Zenith Antenna (MLHZA, or HZA for short), is a two element cross-v dipole used to include SV measurements from 40 to 90 degrees in elevation. This HZA is mounted on top of the stacked dipole array with a feed that runs inside the null chamber (center) of the 8-foot tall bottom segment. The HZA provides at least 20 dB of direct to indirect pattern isolation.

Although the top and bottom IMLA segments are used to include pseudorange measurements from 5 to 40 and 40 to 90 respectively the patterns of each segment are somewhat wider. The overlap region is a critical part of the IMLA's design and in reality amounts to approximately 26 degrees, centered at about 29 degrees in elevation.

5.2.2 Reference Station Receive and Transmit System

At the heart of the LTP's four reference stations is a dual deck, 12-channel, narrow correlator, GPS receiver tied to a common clock. The dual deck design accommodates the IMLA's two feeds, while the common clock ensures that the pseudorange measurements on both decks are taken simultaneously. A final calibration in the Master Station software is performed using an SV that is common to both decks which removes any remaining hardware biases. The current version of the receiver firmware is 7.51s9.

Data to and from the reference stations are put on fiber lines, which run through media converters (fiber to copper), which provide a RS-232 serial signal to the receiver communications port and master station CPU.

Surge and back-up power protection is present on all active reference station components.

5.3 Field Monitoring Stations

The LTP's operation and performance is closely monitored with several dedicated systems. This section outlines the two major monitoring tools that provide an instantaneous performance indication as well as post data processing capability.

Raw monitoring station data collected is useful for observing variations in the differential position since the position can be compared to the survey position of the fixed GPS antenna. Also, it provides a continuous position calculation reference in the absence of actual flight-testing.

5.3.1 Multi-Mode Receiver (MMR) Station

The first LTP monitoring station is a static ground based MMR system. The LAAS T&E team maintains an MMR on a precise surveyed GPS antenna to monitor ground station performance and to evaluate MMR software updates. The MMR drives a dedicated Course Deviation Indicator (CDI). The CDI is a cockpit instrument that indicates fly left/right and up/down information with respect to the intended flight path. The CDI should always be centered when the MMR is tuned to the virtual runway that coincides with the antenna's survey position. The version of MMR firmware for this reporting period is Flight Change (FC) 03.

5.3.2 LTP Airborne Station

The second monitoring station is an LTP airborne subsystem (LTP Air). The LTP Air is a prototypical mock-up with navigational capabilities similar to that of the MMR. The LTP Air, however, provides more configuration flexibility than the MMR and serves well as an R&D tool. These systems are used for actual flight-testing, and for MMR update verification or troubleshooting. This dedicated LAAS field monitor, as the MMR, is placed on a precise surveyed GPS antenna. Data is collected in 24-hour intervals without interruption and is used to post evaluate system navigational performance. Live data is also fed via a wireless network and is available via the Internet. This data is displayed is graphic form and provides the user a daily performance history glimpse. All major performance parameters, available to an airborne user, are displayed. The web address for this live service is: http://www.gps.tc.faa.gov/technical.htm.

The LTP Air system is the LTP's primary performance field monitoring tool. The operational configuration of this system is briefly described in the following text. The custom program initializes all the variables, sends the initialization commands to the VHF Data Link (VDL), and opens up the necessary files. The GPS receiver and VDL are connected to a multi-port RS-232 serial card, which multiplexes the inputs and connects to the computer. The messages are then parsed out according to the type, and processed accordingly. The GPS messages are then split into the different GPS message types (range, ephemeris, clock...etc) and the VDL messages are separated into each of the DO-246B LAAS message types and decoded. Next the satellite position is calculated using the range and ephemeris messages from the GPS measurements. The position of the aircraft is determined and a differential position is calculated based on the measurements from the LGF. Protection levels are calculated for the aircraft and compared to current threshold alarm levels while the satellite measurements are also checked for errors.

To drive the LTP Air's Course Deviation Indicator (CDI), an output message is constructed and is sent via the RS-232 card to an analog conversion unit. The display screen is updated to reflect the new data, and the user inputs are processed. If the program continues with no errors or user input to terminate the program, it retrieves another message from the serial buffer and begins the process again. The LTP airborne internal RCS version number for this reporting period is 1.8.

5.4 L1/L2 Ionospheric (IONO) Station

A separate, but equally important, station is maintained at the FAA's LTP to conduct, centimeter level post processing performance analysis down to a single SV observable on a single reference antenna segment.

This station is referred to as the IONO (short for ionospheric) station (see Figure 1). The name is largely due to the purpose of observing the ionospheric propagation delay, as well as other path delays. The L2 carrier observable (L2 code is unobservable for civilian use) is useful in determining propagation delays in the L1 carrier due to the frequency difference in L2. The L1 frequency is centered at 1575.42 MHz, while the L2 center is at 1227.60 MHz. Since both signals originate from the same point and time the difference in the signal's different arrival times can be used to extrapolate the actual path delay. The determined delay covers the ionosphere path as well as multi-path and other delays. This total delay, due to the signal path length, and short baselines, can be applied to all 8 RRA segments.

See Section 8.1 Code-Minus-Carrier (CMC) area for further detail on where the IONO data is applied.

The IONO station can also serve as a full time L1/L2 reference station for local survey work and aircraft tracking processing. Both activities require a static L1/L2 data collection setup on a known (surveyed) point. This static L1/L2 station data can then be merged, after the fact, with the dynamic (aircraft) data or the unknown static (survey) point data to determine precision aircraft path or survey position figures.

5.5 Testing Activities

The LAAS T&E team is responsible for verifying the performance of experimental LAAS hardware and software. Any changes in configuration or degradations in performance are captured and rigorously analyzed. This section outlines testing activities for the reporting period

5.5.1 IMLA Radome Comparison Study

An ongoing testing activity, which began in summer of 2003, was conducted to closer investigate an observed performance variation with the IMLA's new type double-walled radome. A radome is an electro magnetically transparent material (within a specific frequency range) used to protect an antenna's innards. The subject radome was the one protecting the vertical stacked dipole (bottom) segment. The original version of the IMLA included a single-walled radome. This original version reliably passed the LAAS Category (Cat) I Ground Accuracy Designator (GAD)-C curve (refer to Section 8.4.1.6), for C-curve trace) performance constraints, but had insufficient stiffness for required airfield wind loads. The manufacturer addressed this specification requirement with a double walled radome. Initial accuracy testing was acceptable, but at a degraded level, and varied over time.

Performance analysis monitoring of a new type IMLA with a double wall radome indicated variations that often exceeded LAAS GAD-C constraints. Initial testing began in June of 2003 at LTP site LT2. At that time the remaining three reference stations had the original single wall radome supplied with the IMLA. After base lining the double wall radome performance for several weeks, follow-on testing of the subject dipole array involved stripping the array of all radome material. The test array was then fitted with an original type single wall radome. The antennas performance was greatly improved and varied little over time indicating that the antenna's innards were unflawed. The test array was then re-fitted with the original double wall radome. Performance of all test case configurations were evaluated and revealed GAD-C satisfaction for all cases, including the refitted radome. Again this performance degraded and varied over time. It was suspected that, over time, condensation was forming between the two radomes, which would act as a signal reflector, causing short length Multipath inside the dual wall air gap.

In Mid-August 2003 all four reference stations were fitted with IMLA antennas with double walled radomes. This allowed more thorough baseline testing of the new type configuration due to the larger sample size in the well-characterized LTP environment. Initial testing in June and July 2003 had prompted the manufacturer to provide the LAAS team alternate radome types for testing at the initial test site LT2. After attempting several manufacturer provided alternate radomes, the LAAS T&E team's data analysis revealed that a prototype vented double wall radome performed the best and with the least variation.

At the beginning of the last reporting period LT2 had a prototype vented radome IMLA installed which was under an extended evaluation. During this time an order for all new IMLA antennas with the final vented radome design, and L1/L2 capabilities, was executed. This new L1/L2 IMLA was installed on March 24, 2004 and was undergoing evaluation at the end of the last reporting period.

Interestingly enough the new type L1/L2 IMLA did not perform as stable as the original IMLA within the vented double wall radome which prompted more testing. Initially it was believed that a new style preamp and filter unit provided with the antenna might need closer evaluation. After several weeks of baseline data collection the IMLA was reconfigured with the legacy type preamp and filter. This changed provided little improvement and attention again turned to the radome, it was suspected that the dewy spring weather might be causing variations even in the presence of a vented double wall radome.

First the dipole segment was fitted with an original style single wall radome, which provided improved performance and greater stability. The dipole was then fitted with the prototype vented double wall radome, which evidenced similar performance as the production version. The dipole was then stripped of all protective radome material during a dry period in late May.

The determination was made that a single wall radome must be reincorporated into the IMLA design. Correspondence with the manufacturer to design a single wall radome with sufficient wind load characteristics took place near the end of this reporting period.

5.5.2 LGF-4 testing

Field-testing of a recently procured dual deck receiver that meets all LAAS specification requirements began at LTP site LT2 on February 4, 2004. The new receiver, referred to as a LAAS Ground Facility (LGF) version 4, provides Signal Quality Monitoring (SQM), and tracking of the WAAS as an additional ranging source (not needed for WAAS correction data). Initial lab and field-testing revealed some shortcomings that involved factory settings and reliable WAAS tracking. Overall performance, however, was most acceptable and a firmware update order was forwarded to the manufacturer on February 27, 2004.

The manufacturer finalized the latest updated firmware version 1000a14 and was received by the FAA on May 16, 2004. Bench testing was conducted immediately and the firmware operated as advertised. LAAS specifics such as a narrow correlator, logs at he appropriate trigger settings, and greatly improved WAAS tracking performance were in evidence. Follow up field-testing at the LTP began at the end of this reporting period.

6. Maintenance

The FAA's LTP requires little maintenance. The system's components do falter on infrequent occasions and require replacement. More common is the need to retrieve the raw archive data, which entails the swapping out an empty external hard-drive.

The LTP is an AOA-installed operational LAAS system and requires the same type of airport maintenance activities required for other AOA-installed systems.

6.1 Routine Maintenance

External hard-drives for raw data collection are switched on a weekly basis, but could go as long as 45 days without this operation. This operation requires an interruption of service due to the hardware limitations inherent to the real time operating system. An interruption of approximately seven minutes is required to perform this operation.

Shrub trimming on the LAAS installation field was conducted from May 8th through May 14th. LTP service continued uninterrupted throughout operations.

Rebalanced input power to front end of receivers at LT1, LT2, LT3, and LT5 on April 7th. This operation is referred as an Automatic Gain Control (AGC) calibration, and is done periodically to address slight drifting in the receiver's automatic front-end. This front-end input level dictates the Carrier-to-noise (C/No) values that are observed which are critical to maintain at a specific maximum, and therefore minimum, level. See section 8.1.4 for additional information on this receiver parameter.

6.2 Upgrades and Updates

6.2.1 Software

Air Segment software was updated on April 3rd to provide an automatic end of week (EOW) transition. GPS time utilized in the LTP and Air Segment is of a seconds of the week base. Every Saturday evening these GPS seconds of the week reaches 604800 and then restarts at 1. This EOW crossover was never accounted for in the prototype software version since it was not required to fly through the EOW, and the fix was moderately complicated.

This update was needed to allow uninterrupted monitoring station data collection during the weekend, and provide a continuous web based monitoring link.

6.2.2 Hardware

A secondary IONO station was added nearby to the LTP to serve as a backup for CMC processing as well as a backup tracking reference. On infrequent occasions the LTP IONO station can crash and may go unnoticed for several days. The LTP IONO station can now serve as the primary, and when backup reference station data is required the primary can continue data collection without interruption.

6.3 Failures and Forced Events

The L1/L2 receiver on the IONO station antenna was replaced on March 31st in an attempt to address excessive dropouts in tracking. Initially performance improved, but after several weeks the intermittent dropouts resurfaced. Additional troubleshooting uncovered an intermittent RF cable link which was immediately replaced.

7. Significant Weather and Other Environmental Events

This section is reserved to highlight any environmental events that drove system performance to inflated or unacceptable levels or caused a system outage. Events of this type are rare but may include: solar flares, ionosphere storms, geomagnetic disturbances, and limited catastrophic weather events.

This reporting period saw a lightning strike on April 30th, which interrupted power for several hours at the LTP. No additional ill effects were in evidence.

8. LAAS Performance and Performance Type (Category)

The GPS Standard Positioning Service (SPS), while accurate, is subject to error sources that degrade its positioning performance. These errors sources include ground bounce multi-path, ionospheric delay, and atmospheric (white) noise among others. The SPS is therefore insufficient to provide the required accuracy, integrity, continuity, and availability demands of precision approach and landing navigation. A differentially corrected positioning service, with short baselines to the user(s), is suitable to provide precision guidance.

The relatively short baselines between the user and the LAAS reference stations, and custom hardware and software, is what sets LAAS apart form WAAS. Special LAAS hardware such as the IMLA serves to mitigate the multi-path problems, while the LAAS software monitors and corrects for the majority of the remaining errors providing the local user a precision position solution.

The LAAS Ground Facility (LGF) is required to monitor and transmit data for the calculation of protection parameters to the user. The LAAS specification also requires monitoring to mitigate Misleading Information (MI) that can be utilized in the position solution. These requirements allow the LAAS to meet the accuracy, integrity, availability, and continuity required for precision approach and landing navigation.

There are three Performance Types (PT) defined within the LAAS Minimum Aviation System Performance Standards (MASPS). The three performance types, also known as Categories, (Cat I, and Cat II/III) all have the same parameters but with different quantity constraints. For the purposes of this report, the LTP assumes Cat I Alert Limits and hardware classification.

8.1 Parameters and Related Requirements Overview

This section highlights the key parameters and related requirements used to depict LAAS system performance in this report. In order to provide the reader a clearer understanding of the plots provided, a little background is useful.

Cat I precision approach requirements for LAAS are often expressed in terms of Accuracy, Integrity, Availability, and Continuity. For clarity the use of these four terms, in the context of basic navigation, are briefly described below:

- **Accuracy -** is used to describe the correctness of the user position estimate that is being utilized.

- **Integrity** – is the ability of the system to generate a timely warning when system usage should be terminated.

- **Availability** - is used to describe the user's ability to access the system with the defined Accuracy and Integrity.

- **Continuity** - is used to describe the probability that an approach procedure can be conducted, start to finish, without interruption.

Parameters used to depict LAAS performance in the remainder of this report are outlined below:

8.1.1 VPL and LPL

Accuracy for a Cat I LAAS is best quantified in terms of the vertical and lateral Navigation System Error (NSE). LAAS position is translated into vertical and lateral components of error with respect to the pre-defined path in space. The 95% limits for lateral and vertical NSE defined in the LAAS MASPS are used as a performance measure. The 95% Vertical NSE limit tightens as the user descends toward the Runway Datum Point (RDP) on the final approach path. For heights above the RDP of 1290 ft or more, the Vertical NSE limit is 16.7 meters. For heights between 1290 and 200 feet the vertical NSE limit begins at 16.7 meters (at 1290 feet) and traces a straight line down to 4 meters (at 200 feet). This 4-meter Vertical NSE limit is maintained to 100 feet above RDP along the final approach path. The 95% Lateral NSE limit is similar in construct, but is related to horizontal distance from the RDP along the final approach path. For distances beyond 7212 meters the Lateral NSE limit is 27.2 meters. For distances between 7212 and 873 meters the Lateral NSE Limit begins at 27.2 meters (at 7212 meters) and traces a straight line to 16 meters (at 873 meters). This 16-meter Lateral

NSE Limit is maintained to 291 meters from the RDP along the final approach path. Vertical/Lateral NSE and Vertical/Lateral Protection Levels (VPL and LPL) are closely related. The user's Vertical/Lateral NSE can only be determined through post processing with a precision truth tracking system. The FAA has processed hundreds of actual LAAS approaches, and monitoring station data sets, to verify the 95% Vertical/Lateral NSE of LAAS. The 95% NSEs obtained must be bounded by the user's computed VPL and LPL (a.k.a., HPL). These Protection Levels are in turn bounded by the corresponding Alert Limits. It has been shown that the NSE performance is easily within the MASPS requirements, and the need for splaying is a benefit only when it comes to the integrity bound that must be computed based on a real-time estimate of the user's position.

Integrity for LAAS is associated with known failure modes within the system and the monitors that are designed to detect the failures before it is manifested in the airborne receiver as Misleading Information (MI). Each failure mode has an associated monitor that is assigned a corresponding probability of the failure occurring, or a prior probability, and an associated probability that the failure is detected, or a missed detection probability. The Cat I LAAS specification states "the probability that the LGF transmits Misleading Information (MI)…shall not exceed 1.5X10^(-7) during any 150-second approach interval". The LAAS MASPS defines MI as a Navigation System Error, which exceeds the Vertical or Lateral Alert Limits (VAL or LAL) without annunciation within the time to alert (3 seconds). The VAL and LAL are fixed at 10 and 40 meters (radius) respectively. These limits are not to be exceeded by the user's calculated Vertical and Lateral Protection Levels (VPL and LPL) bounds. The VPL and LPL are upper confidence bounds on the positioning error with specified probabilities. The NSE is bounded by the Protection Levels, which are in turn compared to the Alert Limits. If the user's Protection Levels exceed the Alert Limits the approach is flagged within the time to alert of 6 seconds. There are actually a number of parallel hypotheses (see LAAS MASPS) used in determining the user's Protection Levels. The VPLmax and LPLmax (worst case) calculation is the level that is applied for comparison to the alert limits. In basic terms, the relation is as follows:

Vertical NSE < VPLmax < VAL = 10 meters
Lateral NSE < LPLmax < LAL = 40 meters

Continuity and *Availability* are related, but are not interchangeable. A system must first be available before you can determine if it meets continuity. LAAS may be available at the initiation of the approach, but a unfavorable constellation change or other event may make the approach unavailable before it is completed. Therefore, this approach would suffer a loss of continuity. For the purposes of this report Availability and Continuity are analyzed in terms of LAAS Protection Levels that are within the alert limits for a given time period (24 hours). The LAAS MASPS states, for Cat I, that "the overall probability of a loss Continuity due to a Protection Level exceeding the Alert Limit shall not exceed 7.8X10^(-6) per 15 seconds". A properly configured and maintained LAAS, such as the FAA's LTP, can meet this constraint without any difficulty. The 24-hour VPL/HPL plots provided in this report are most stable and repeatable, and in fact appear identical from one day to the next. Long and short-term system Availability is difficult to quantify for a prototype system such as the LTP, and is accordingly out of the scope of this report.

Section 6, most notably section 6.3, is intended to provide the reader a glimpse at the events that effect the Availability of the LTP system.

8.1.2 VDOP and HDOP

Vertical and Horizontal Dilution of Precision (VDOP and HDOP) parameters of the SPS is actively monitored since the LAAS is required to perform with a worse case constellation and geometry. VDOP/HDOP parameters are directly tied to constellation geometry, and when combined with pseudorange errors affect the SPS position estimate and time bias. Diverse constellation geometry will provide less dilution, while confined constellation geometry will drive dilution higher. What is ultimately diluted is the user's uncorrected Vertical and Horizontal position estimate. Monitoring the VDOP and HDOP in the LAAS ground station gives a valid picture of what the user is experiencing and provides a quantity to the DOP components of error that is experienced prior to applying to a differential correction.

8.1.3 Clock Error

The average Clock Error is important to monitor since rapid changes in the ionosphere can drive the clock error to unusual levels. For the purposes of this report the clock error is presented solely to present a history of a typical clock error condition on a typical day. Clock error will invariably rise when the Total Electron Count (TEC) of the ionosphere is high (day), and fall when the TEC is lower (night). The derived average system clock error is correctable and in general amounts to between 5 and 15 meters (between 0.166 and 0.550 nano-seconds). Much larger clock biases are tolerable as well. The reference receiver clock biases are largely removed from the pseudorange correction (PRC) before these corrections are sent to the airborne equipment. Each PRC measurement may contain a residual clock error that is not removed. The residual clock error is relatively small and complicated to accurately measure. Therefore an estimate of the PRC error (referred to as a B-Value) is calculated elsewhere in the system and is software monitored to actively exclude any single measurement(s) that exceeds a given threshold. Deviations from the cyclical and roughly sinusoidal shape and magnitude of the graph will likely indicate a disturbance that will prompt further investigating to see if other parameters were adversely affected.

8.1.4 Code-Minus Carrier (CMC) and Reference Segment Status

(**CMC**)[2] values are computed for each SV on each antenna segment (eight total, two per reference). The initial CMC quantity is computed by converting the L1 Carrier phase into a range and subtracting it from the Code range (also known as the pseudorange). Additional processing is required to isolate the code Multipath and noise components, which include subtraction of the sample-mean to remove the carrier phase integer ambiguity. Further computation is required for the removal of the ionospheric delay. The ionospheric delay is computed from the L1/L2 carrier phase measurements obtained from the L1/L2 IONO station (see Section 5.4).

[2] CMC – For in-depth explanation on this method refer to ION Navigation Journal, Winter 94/95, volume 41, Number 4, page 415, "Isolation of GPS Multipath and Receiver Tracking Errors" (Braasch).

The CMC values have had the effect of ionospheric delay (as determined from the L1/L2 IONO antenna data) removed from it, and has been smoothed. The CMC value can therefore be considered error that is uncorrectable, and uncommon to the ground station and airborne user. This uncorrectable error consists primarily of Multipath, noise, and hardware biases. The error is minimized by custom LAAS hardware design and adherence to the LAAS siting requirements.

Due to the configuration and siting of the reference stations of the LTP the typical antenna segment error reported has a standard deviation trace residing in the 0.05-meter region. The CMC values and statistic plots are continually monitored to unsure minimum obtainable levels are maintained.

In order to observe overall system performance, the CMC, **number of samples (NOS)**, and **carrier-to-noise** (**C/No**) ratio values from all four reference stations' dipole segments and HZA segments are averaged together so as to create only two sets of data (dipole and HZA) for all SVs, from the original eight antenna segments. C/No is critical to optimum reference receiver (RR) performance, and is closely monitored. The C/No is a density ratio, with units in dB-Hz, and is driven by the amount of total signal power that is permitted to enter two RF inputs of the RR. The LAAS T&E team maintains proper total input power through external attenuation the value of which is obtained by performing an AGC calibration. The NOS also serves as a representation RR performance and health. System level NOS for a given elevation bin is reasonably repeatable for a given GPS constellation. Marked changes in the NOS, without a constellation change, would prompt the LAAS T&E team to investigate and address the potential cause.

Depicted in this section are four ensemble (all data averaged and overlaid) plots that are generated using the data from all SVs over a 24-hour period. Carrier-to-noise versus time and elevation and CMC versus time and elevation, are made up of individual traces for each satellite overlaid atop one another. Also depicted are two statistics plots—mean and standard deviation of the CMC versus elevation bin and number of samples versus elevation bin, combine the data from all available SVs based on their elevation at the time the sample was recorded. For the dipole segment, data is broken into 2-degree bins from 4 to 40 degrees, for the HZA, from 25 to 90 degrees.

The standard deviation of the CMC estimate of pseudorange error is compared to the Ground Accuracy Designator (**GAD**) **"C"- curve**. Any exceedance of the GAD C-curve at the specification required elevations (5 to 40 for dipole, 40 to 90 for HZA, as applied in the LTP) is considered a performance deficiency. These deficiencies are repeatable and will not improve without human intervention. This is when the LAAS team inspects RR/RRA environment and hardware to address the problem.

There are two CMC and antenna segment status sections presented in this report for each month of the reporting period. The first is the dipole antenna section, followed by the HZA antenna section. The CMC process that the LAAS T&E team has developed generates multiple system average plots, which include: CMC error, receiver status, and statistics plots, which are presented together in the CMC sections.

The plot of CMC error magnitude versus azimuth/elevation value shows the performance of each satellite individually, with points on the plot color-coded to the maximum CMC value observed at a given azimuth/elevation pair. Referred to as a "**Characterization Plot**" these figures reveal much about the Multipath environment, and error a SV signal experiences on its path to the receiving element. Any increase in the average reported error indicates a possible problem with the system or environment, which would prompt immediate investigation by the LAAS T&E team.

8.2 Performance Analysis Reporting Method

For a given configuration the LTP's 24-hour data sets repeat performance, with little variation, over finite periods. The LAAS T&E team can make that statement due to the continual processing of raw LTP data, and volume of legacy data that has been analyzed from the LTP by the FAA and academia. Constellation and environmental monitoring, in addition to active performance monitoring tools such as the web and lab resources provide the LAAS T&E team cues for closer investigation in the presence, or suspicion, of uncharacteristic performance.

Data sets from the LTP ground and monitoring stations are retrieved on a weekly basis and are processed immediately. A representative data-day can then be drawn from the week of data to be formally processed. The resultant performance plots may then serve as a snapshot of the LTP's performance for the given week. These weekly plots are afterward compared to adjacent weeks to select a monthly representative set of plots.

8.3 Performance Summary

This reporting period witnessed stable acceptable overall system performance, well within Cat I constraints.

The plots depicted typify historical performance for the current LTP configuration.

No NANUs are highlighted in section 4.3. SV outages experienced for this reporting period caused no interruptions of service.

8.4 Performance Plots

This report provides the reader a LTP system level performance snapshot. For narratives on the utilized parameters refer to Section 8.1 In the interest of space a representative set of plots is chosen on a monthly basis. These monthly plots are presented in the remainder of this section.

8.4.1 Performance Plot Organization

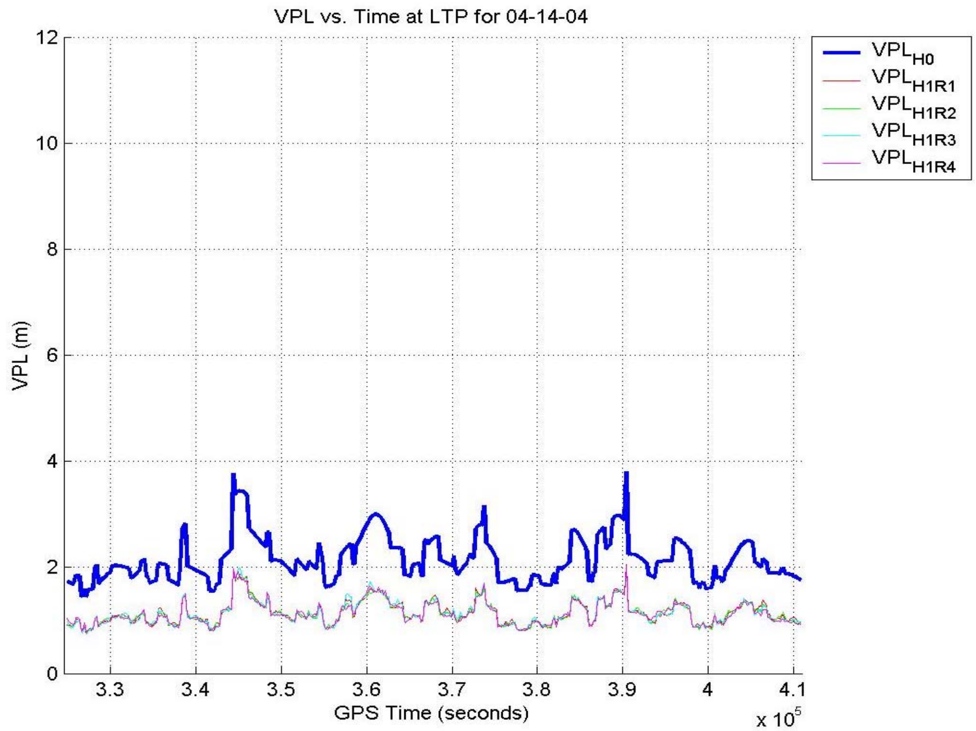
The content and organization of the LTP system performance plots, contained in the remainder of this report, are outlined below.

Reporting Period Month and Year

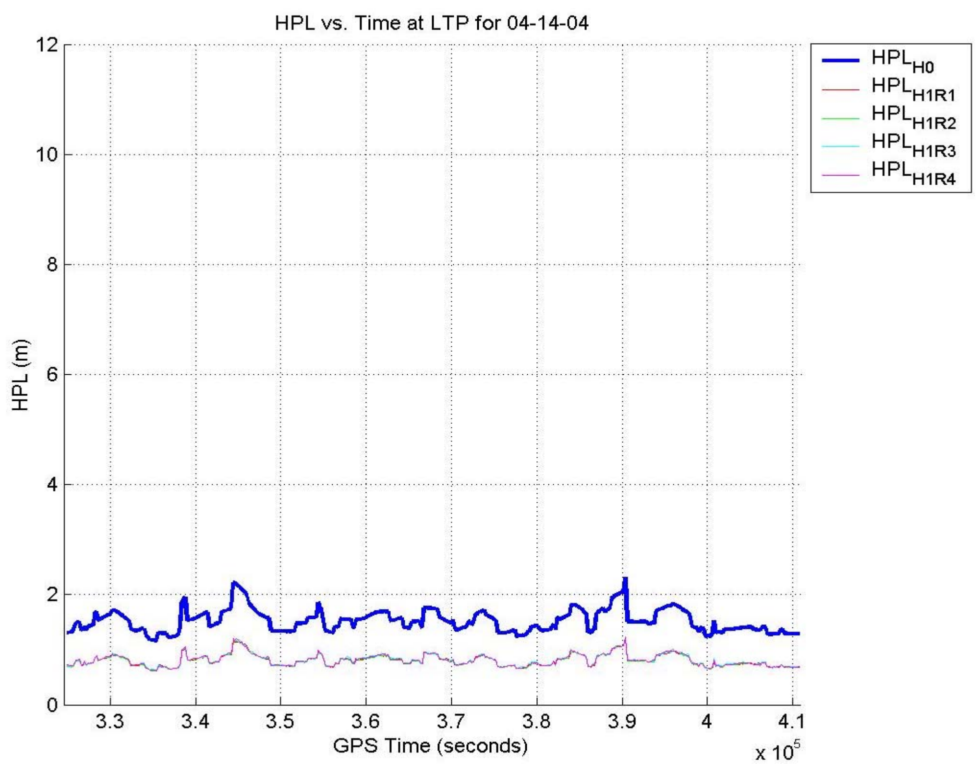
1) **VPL versus Time**
2) **HPL (LPL) versus Time**
3) **VDOP and Number of SV Observations versus Time**
4) **HDOP and Number of SV Observations versus Time**
5) **Clock Error versus Time**
6) **Dipole Status and CMC (System Average) (multiple)**
    - **System Dipole CMC Standard Deviation and Mean versus Elevation**
    - **System Dipole Error Characterization versus Azimuth and Elevation**
    - **System Dipole Number of Sample versus Elevation**
    - **System Dipole CMC versus Elevation**
    - **System Dipole CMC versus Time**
    - **System Dipole Carrier to Noise versus Elevation**
    - **System Dipole Carrier to Noise versus Time**
7) **HZA Status and CMC (System Average) (multiple)**
    - **System HZA CMC Standard Deviation and Mean versus Elevation**
    - **System HZA Error Characterization versus Azimuth and Elevation**
    - **System HZA Number of Sample versus Elevation**
    - **System HZA CMC versus Elevation**
    - **System HZA CMC versus Time**
    - **System HZA Carrier to Noise versus Elevation**
    - **System HZA Carrier to Noise versus Time**

8.4.2 April 2004 Performance Plots

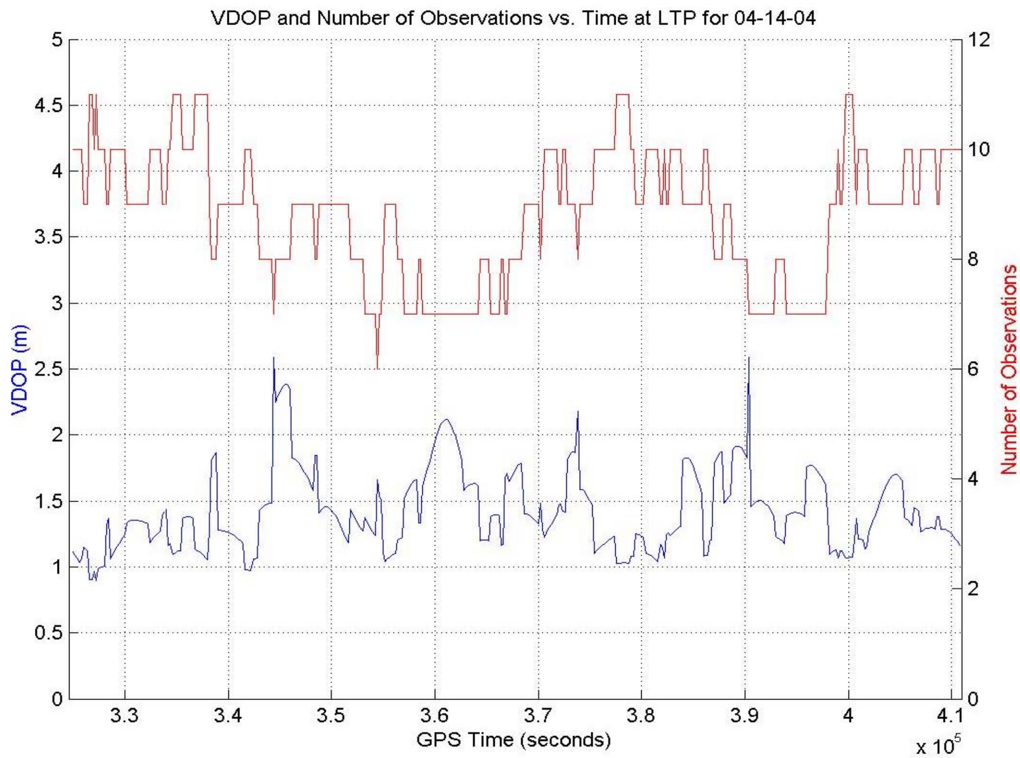
8.4.2.1 April VPL versus Time



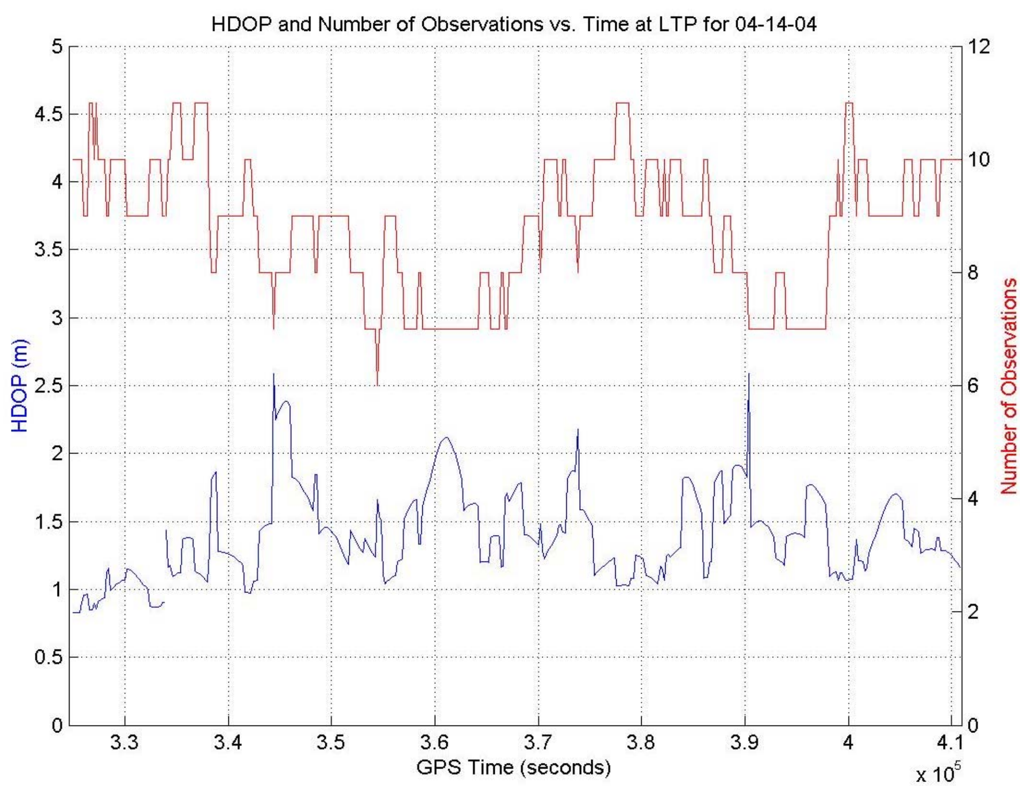
8.4.2.2 April HPL versus Time



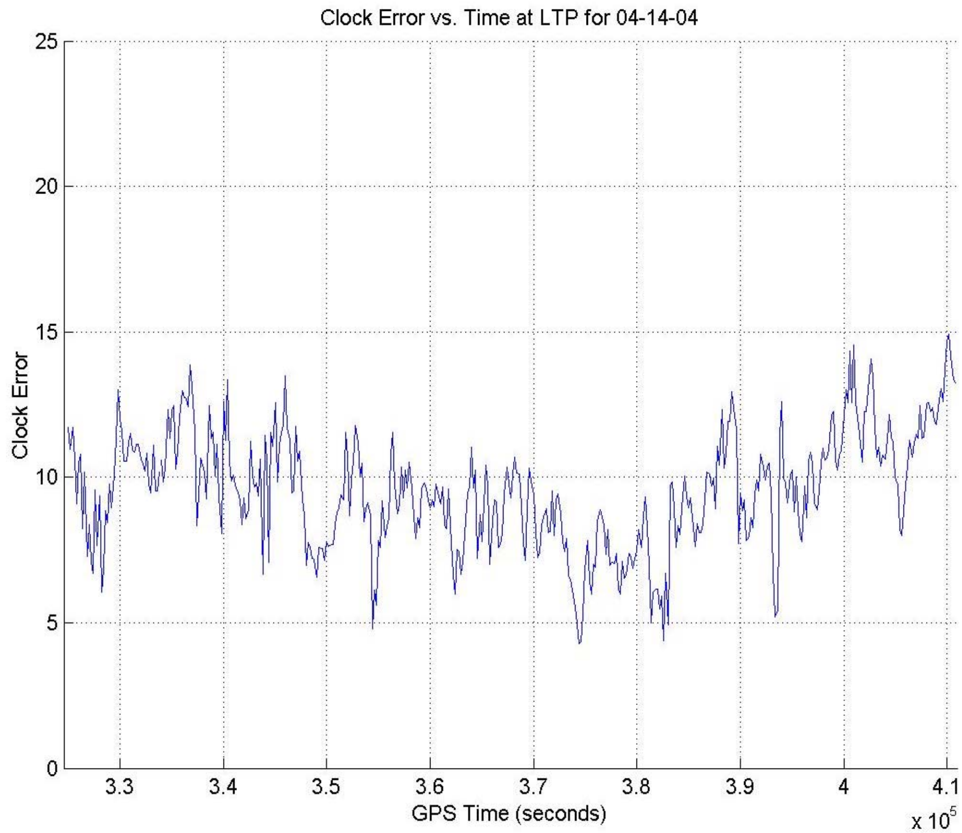
8.4.2.3 April VDOP and # of SV Observations versus Time



8.4.2.4 April HDOP and # of SV Observations versus Time

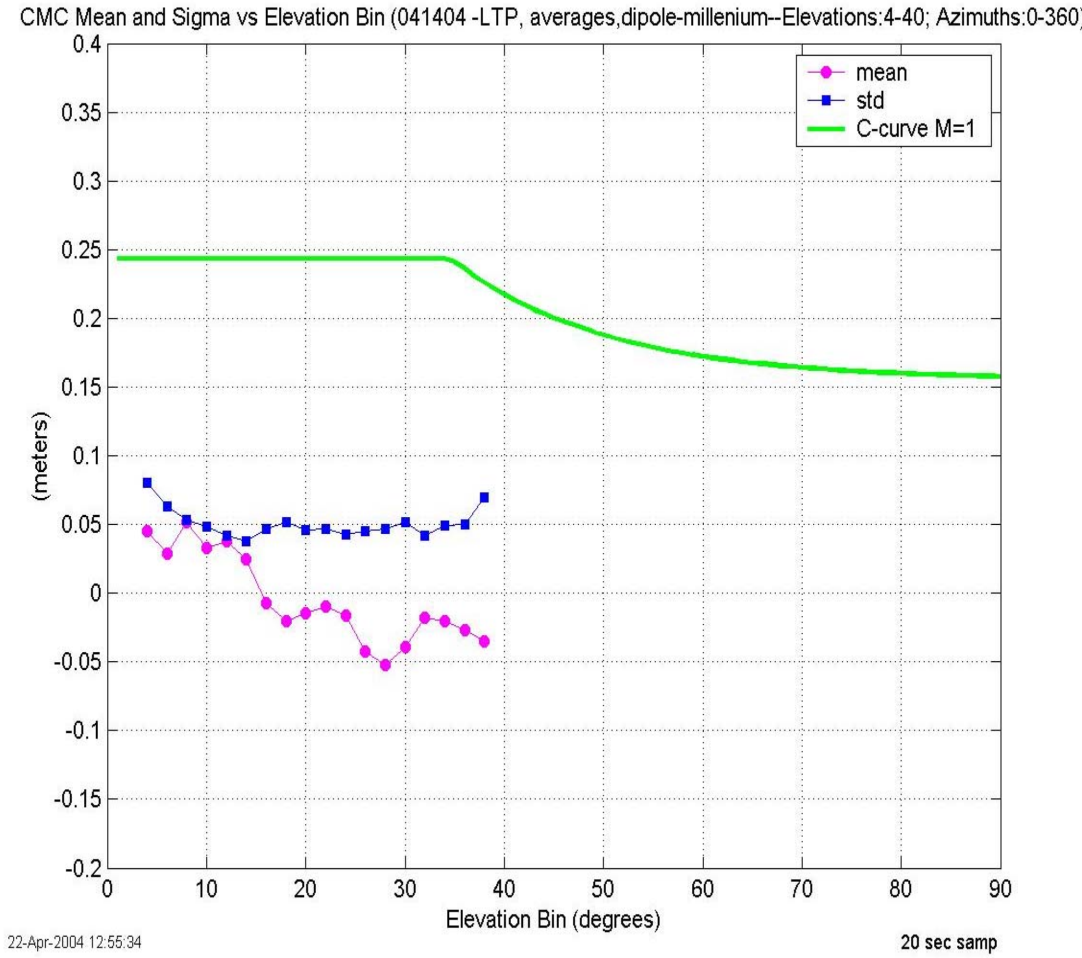


8.4.2.5 April Clock Error versus Time

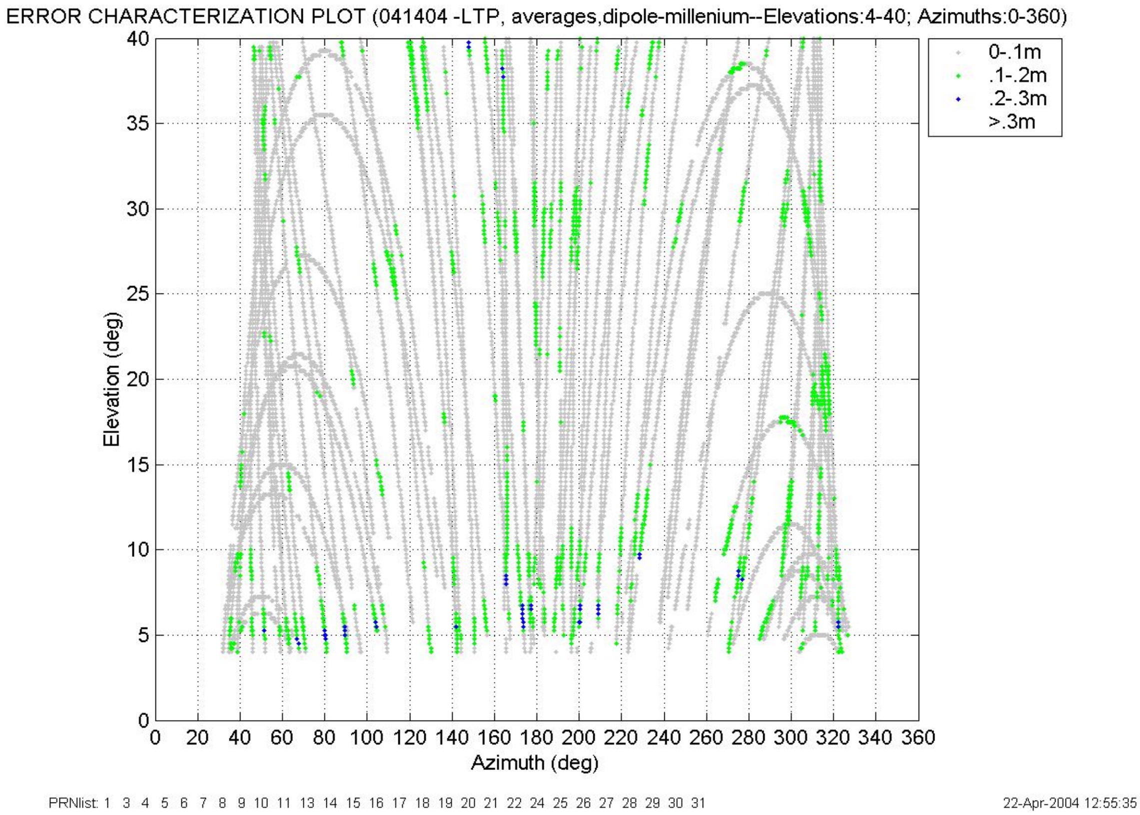


8.4.2.6 April Dipole Status and CMC (System Average) (multiple)

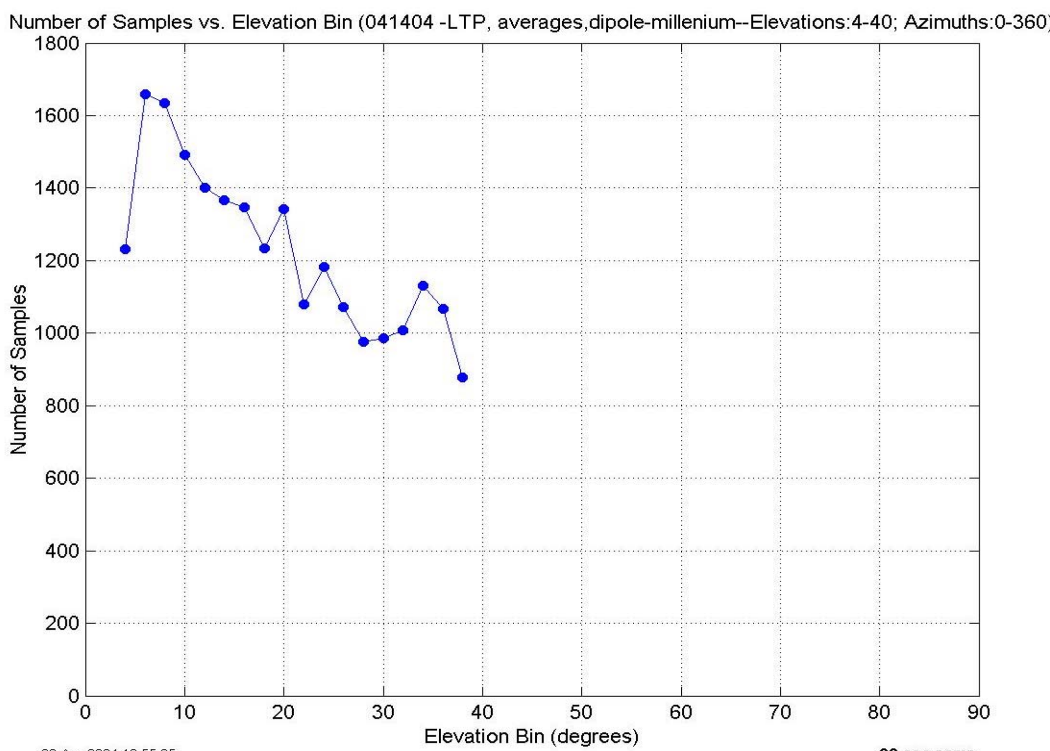
8.4.2.6.1 April System Dipole CMC Standard Deviation and Mean versus Elevation



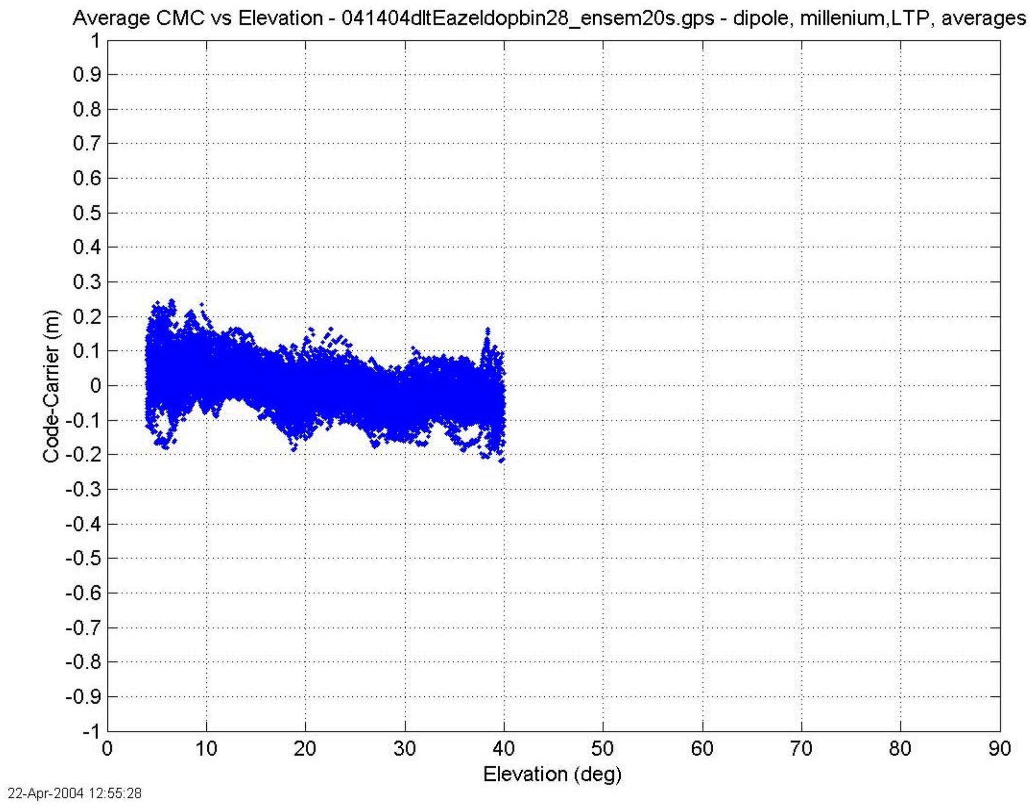
8.4.2.6.2 April System Dipole Error Characterization versus Azimuth and Elevation



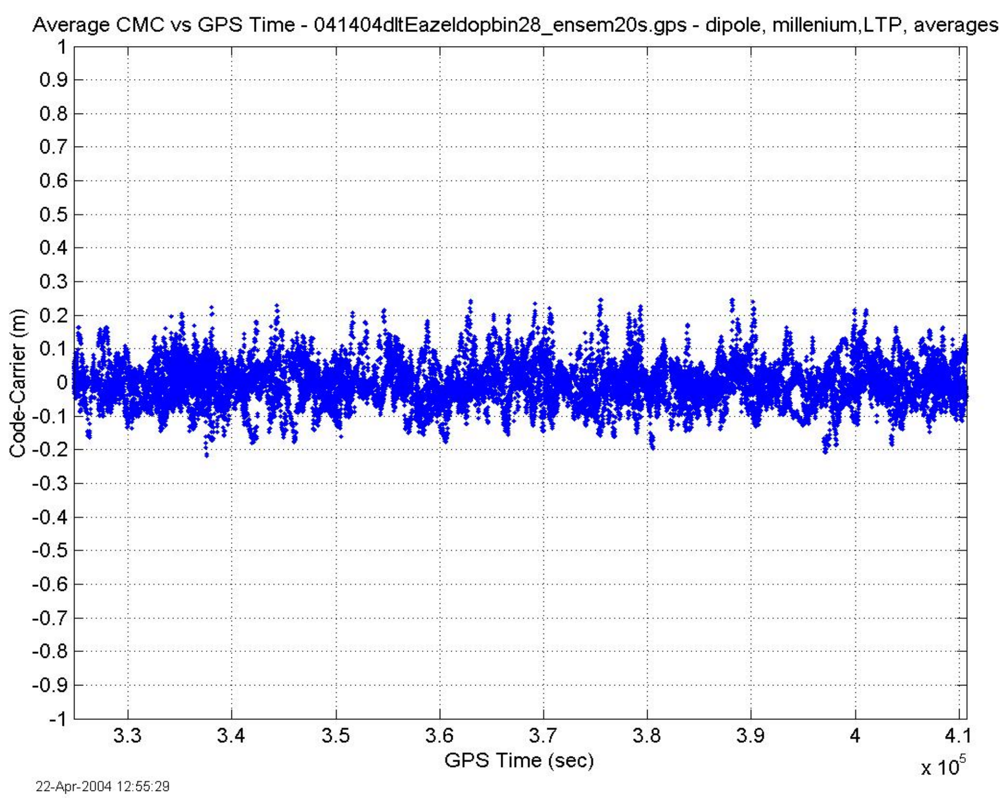
8.4.2.6.3 April System Dipole Number of Sample versus Elevation



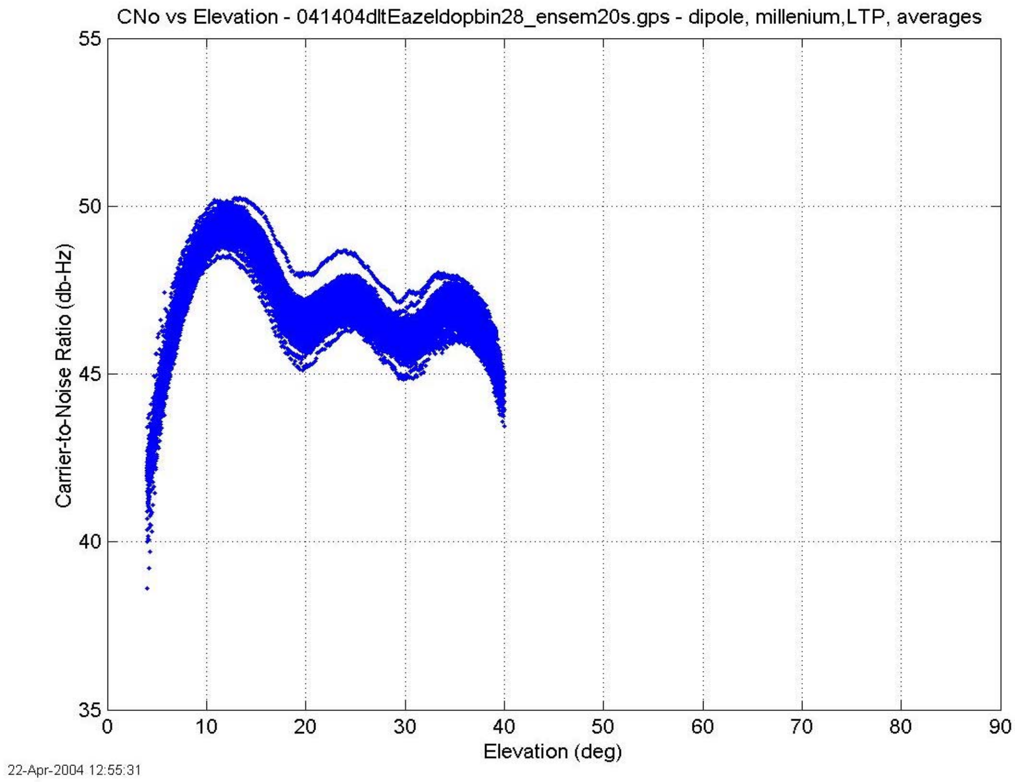
8.4.2.6.4 April System Dipole CMC versus Elevation



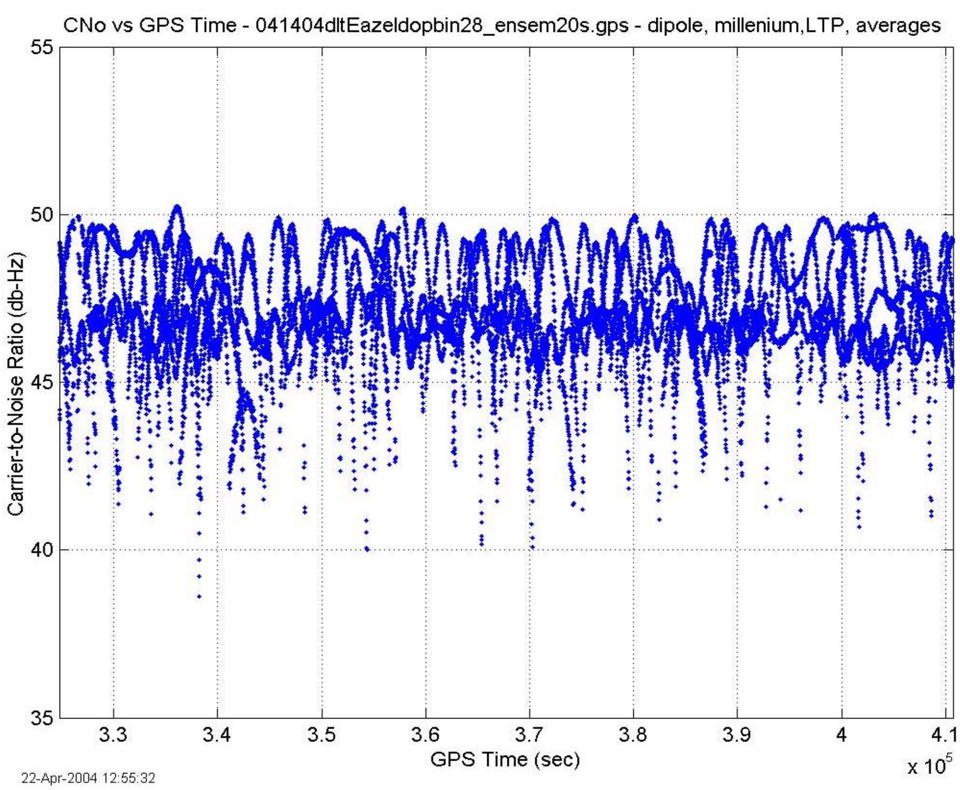
8.4.2.6.5 April System Dipole CMC versus Time



8.4.2.6.6 April System Dipole Carrier to Noise versus Elevation

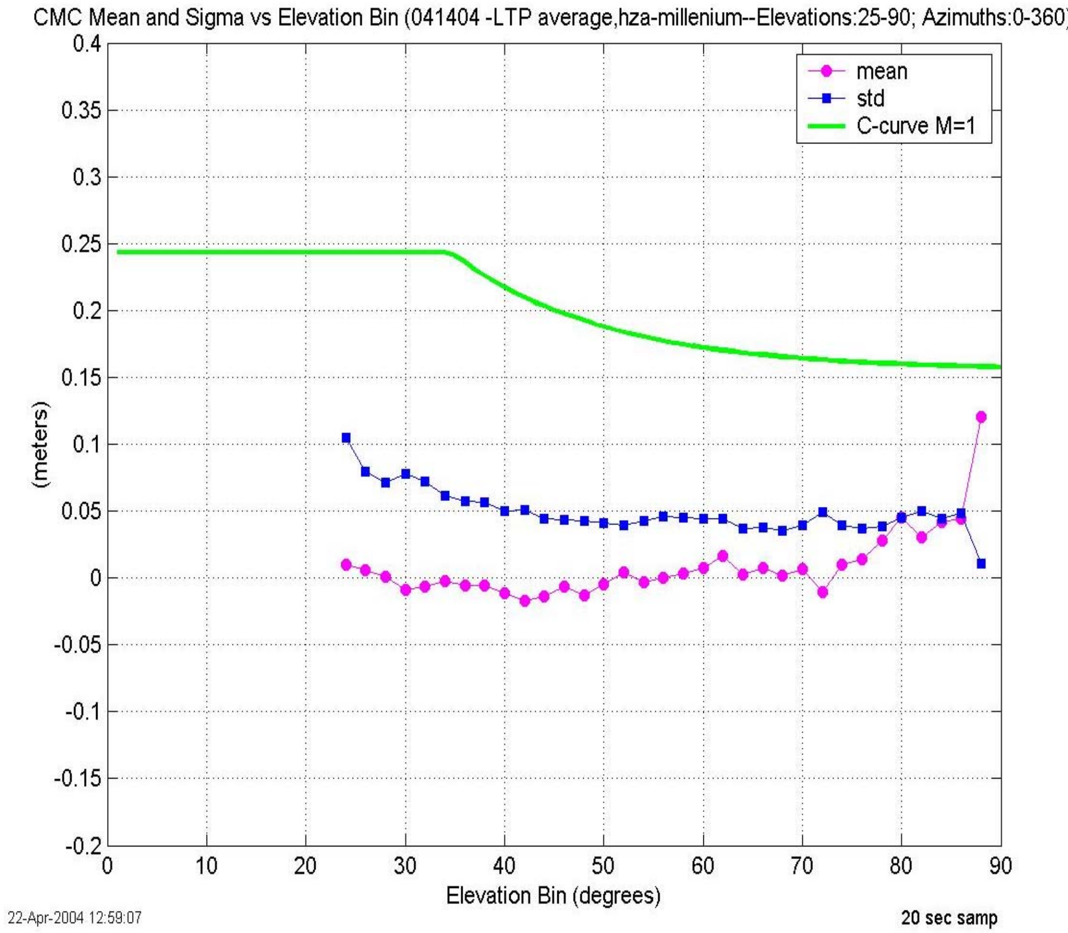


8.4.2.6.7 April System Dipole Carrier to Noise versus Time

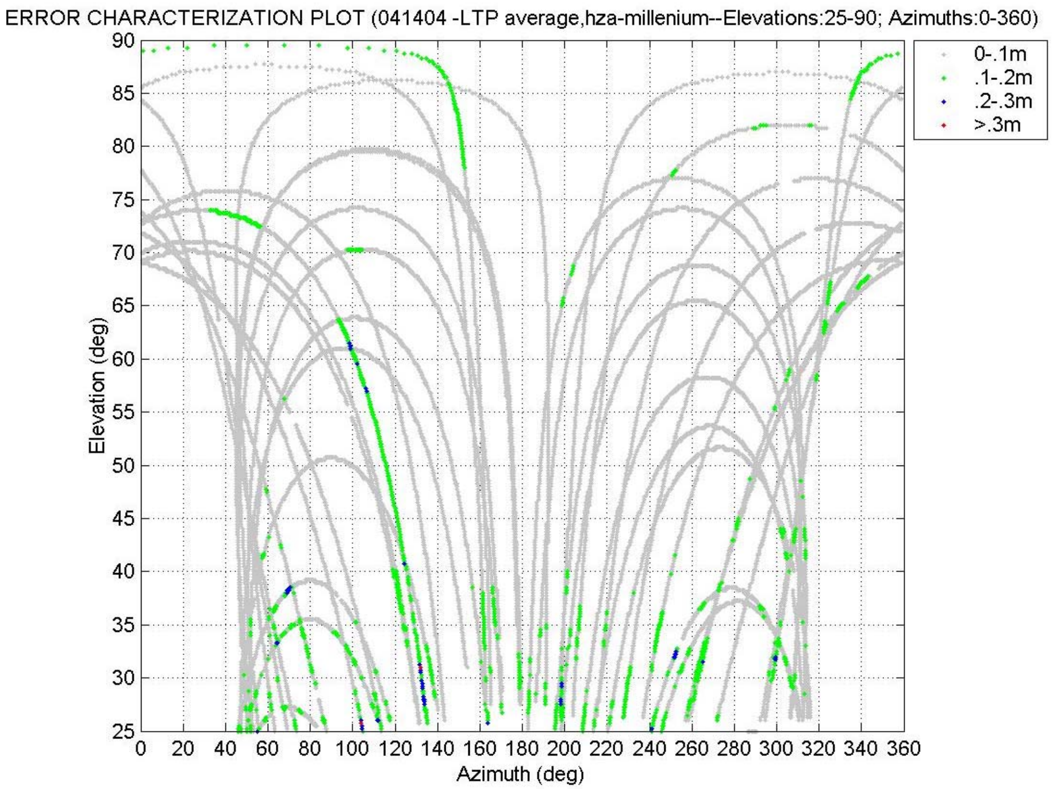


8.4.2.7 April HZA Status and CMC (System Average) (multiple)

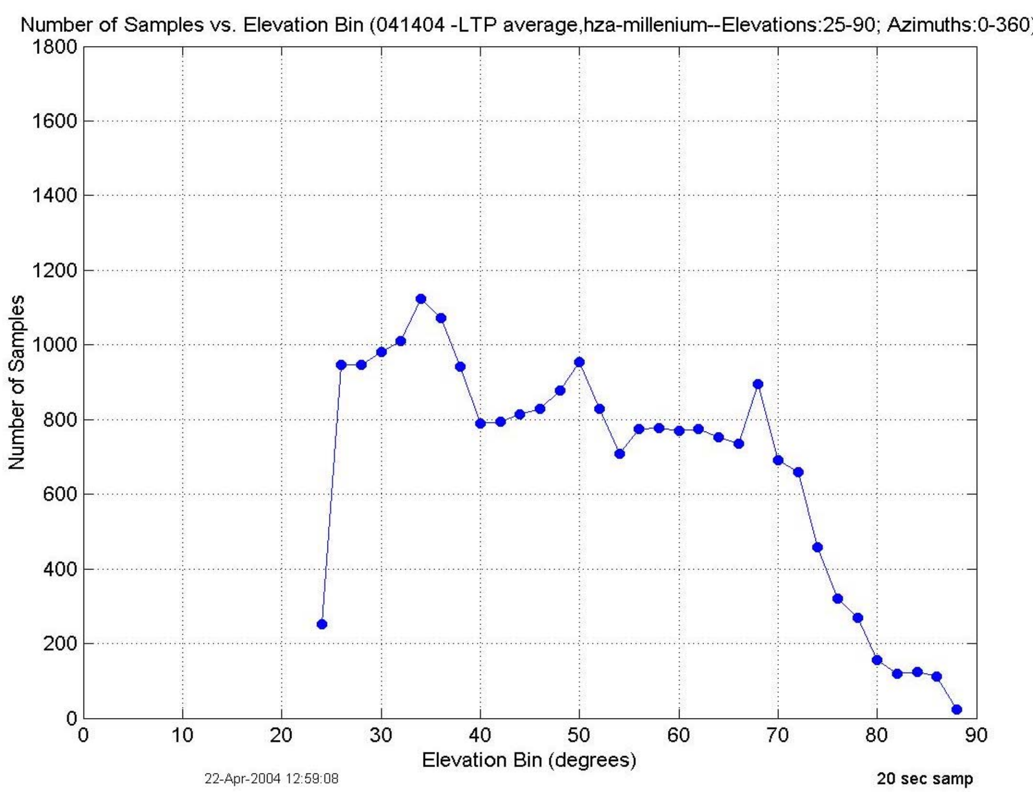
8.4.2.7.1 April System HZA CMC Standard Deviation and Mean versus Elevation



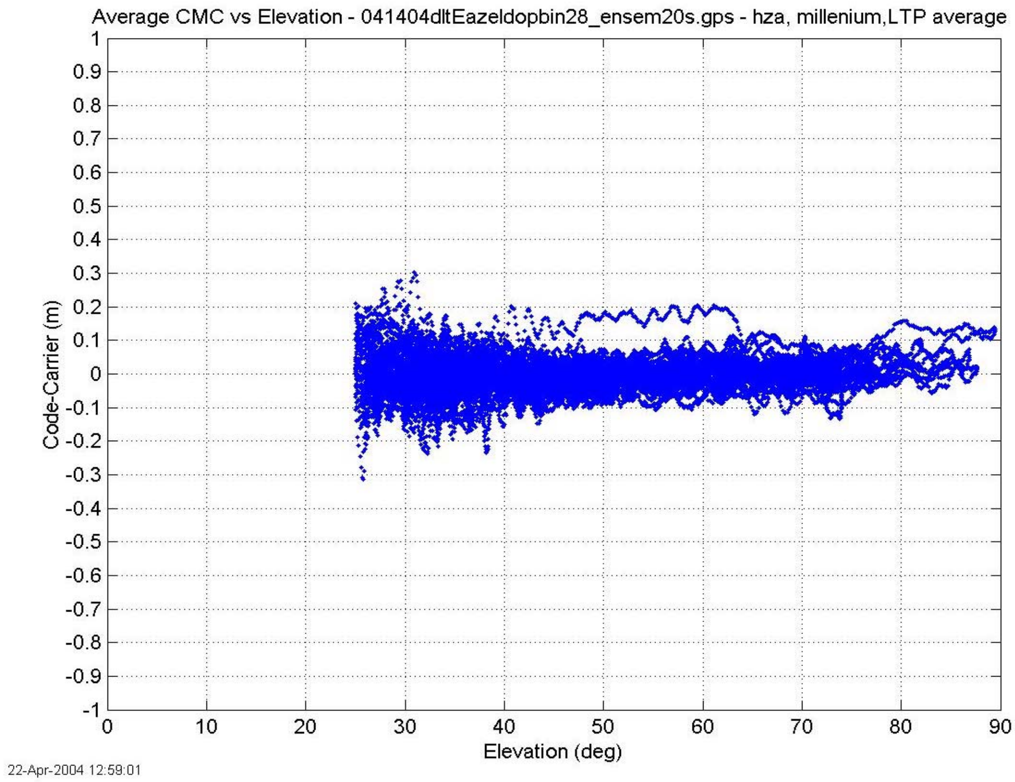
8.4.2.7.2 April System HZA Error Characterization versus Azimuth and Elevation



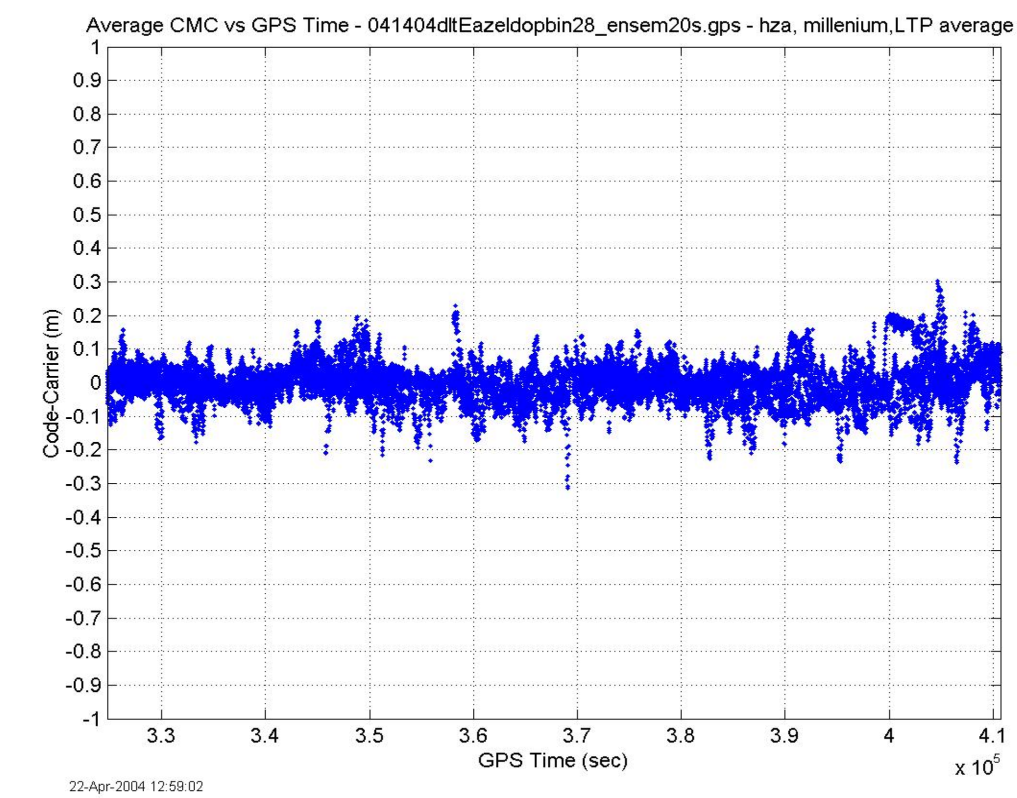
8.4.2.7.3 April System HZA Number of Sample versus Elevation



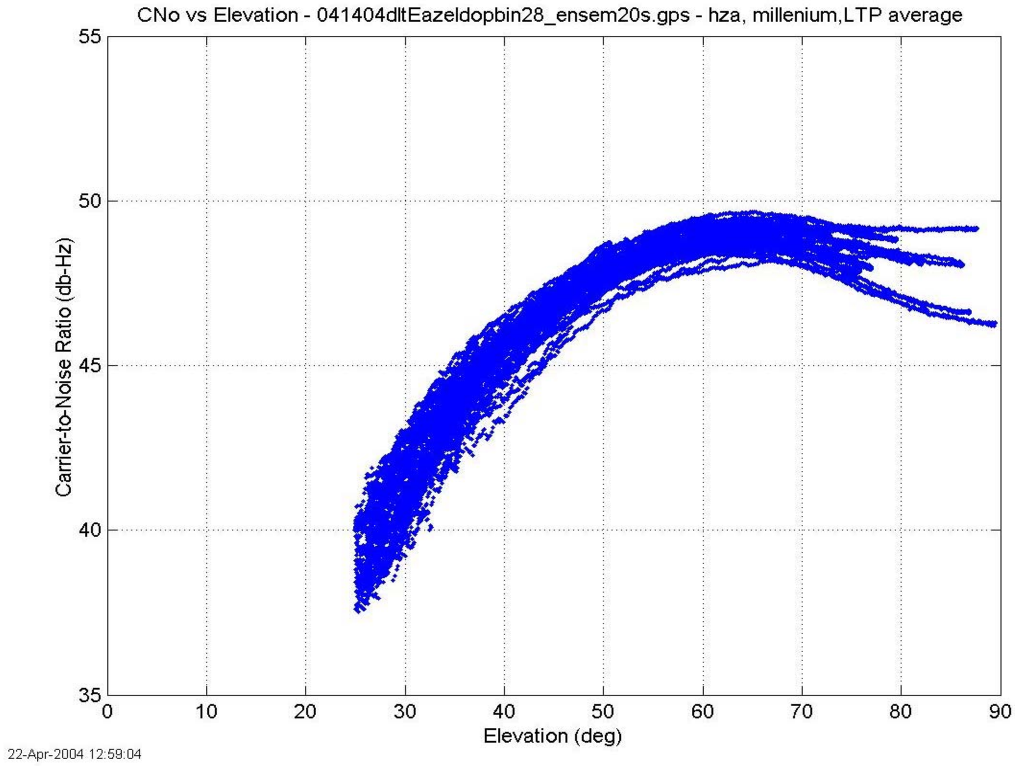
8.4.2.7.4 April System HZA CMC versus Elevation



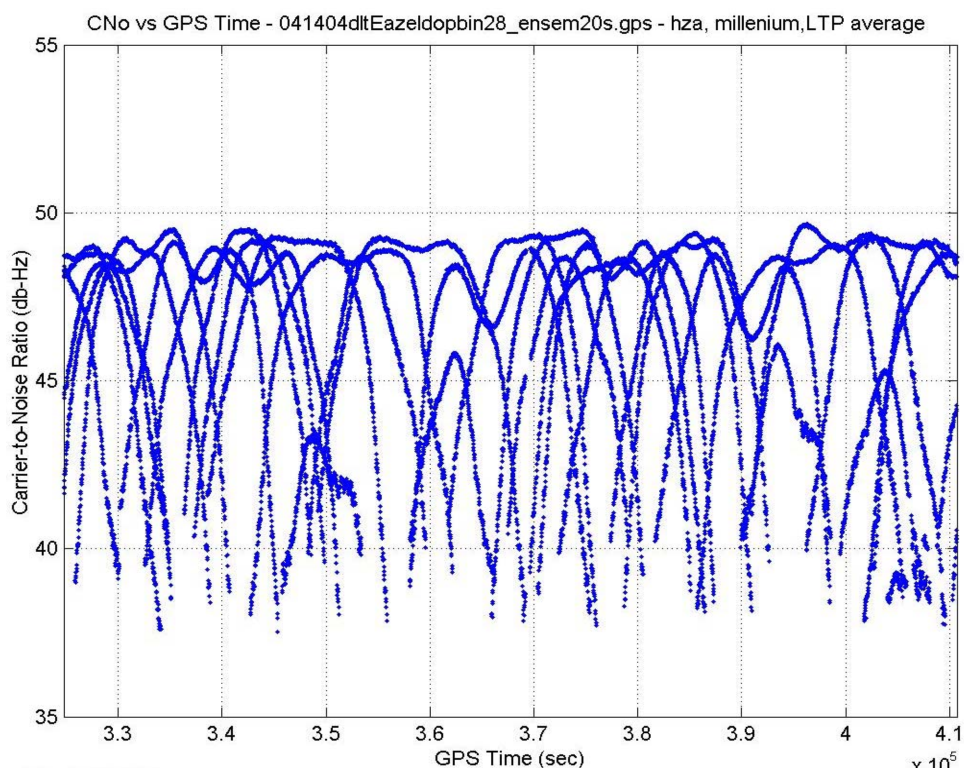
8.4.2.7.5 April System HZA CMC versus Time



8.4.2.7.6 April System HZA Carrier to Noise versus Elevation

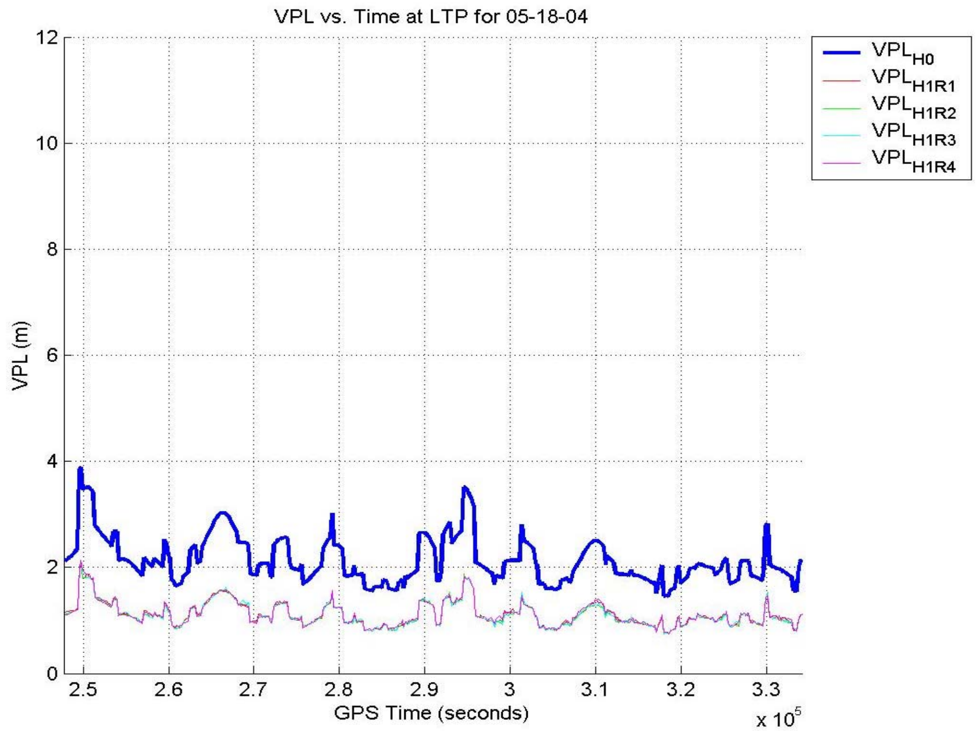


8.4.2.7.7 April System HZA Carrier to Noise versus Time

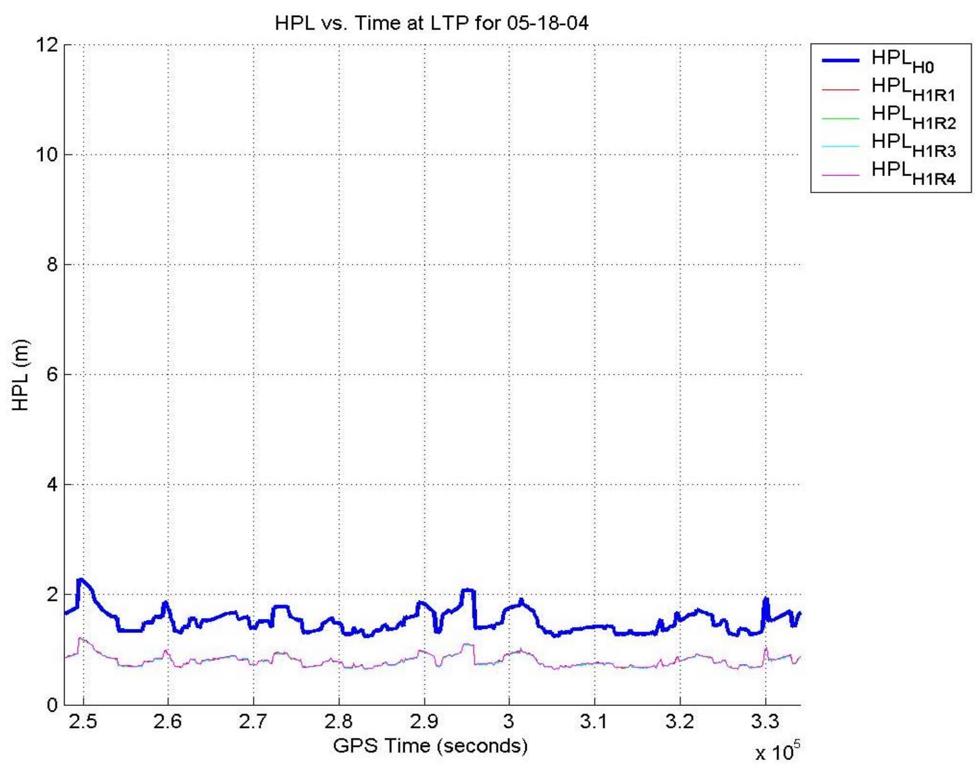


8.4.3 May 2004 Performance Plots

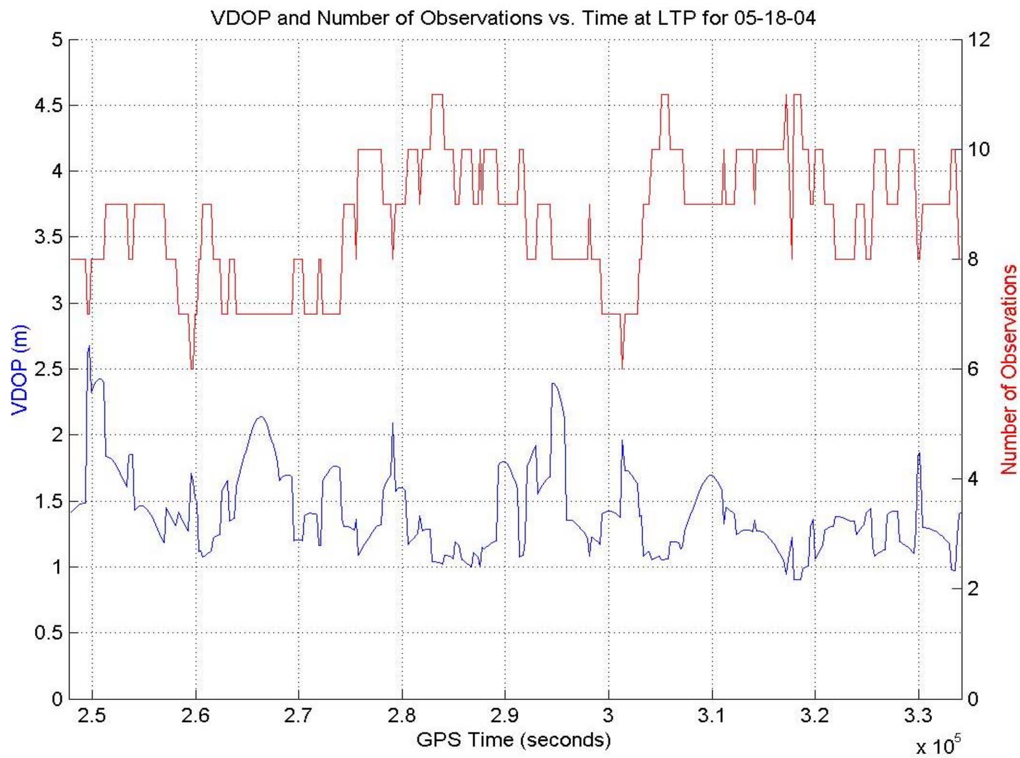
8.4.3.1 May VPL versus Time



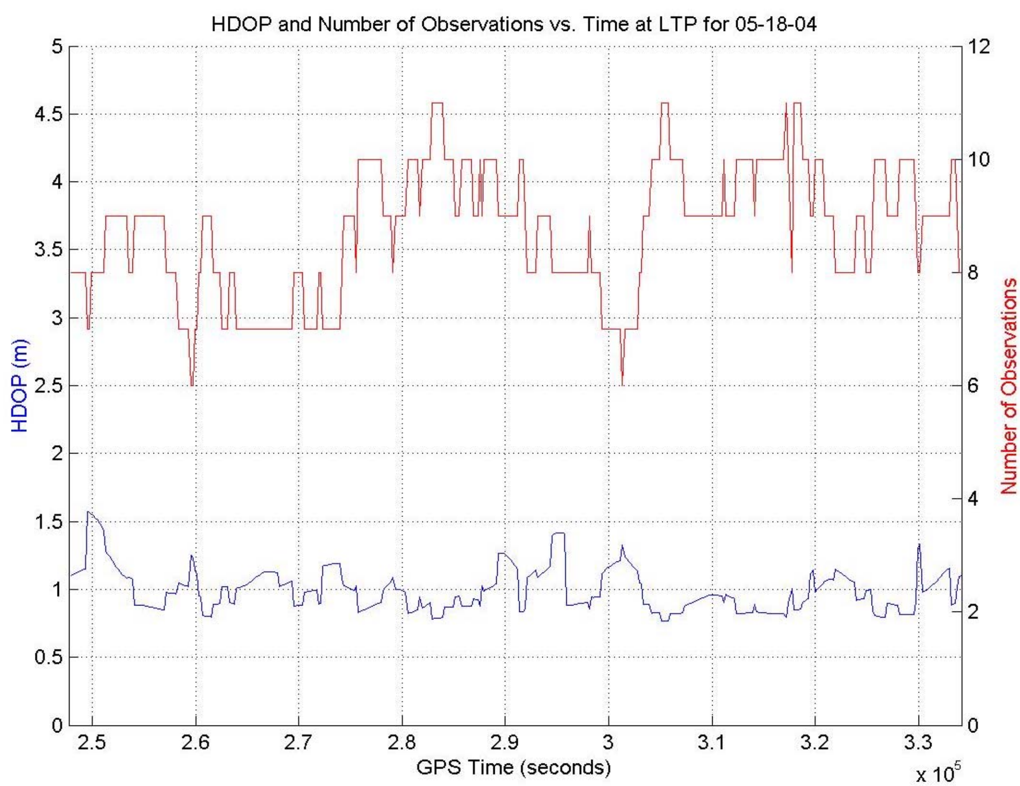
8.4.3.2 May HPL versus Time



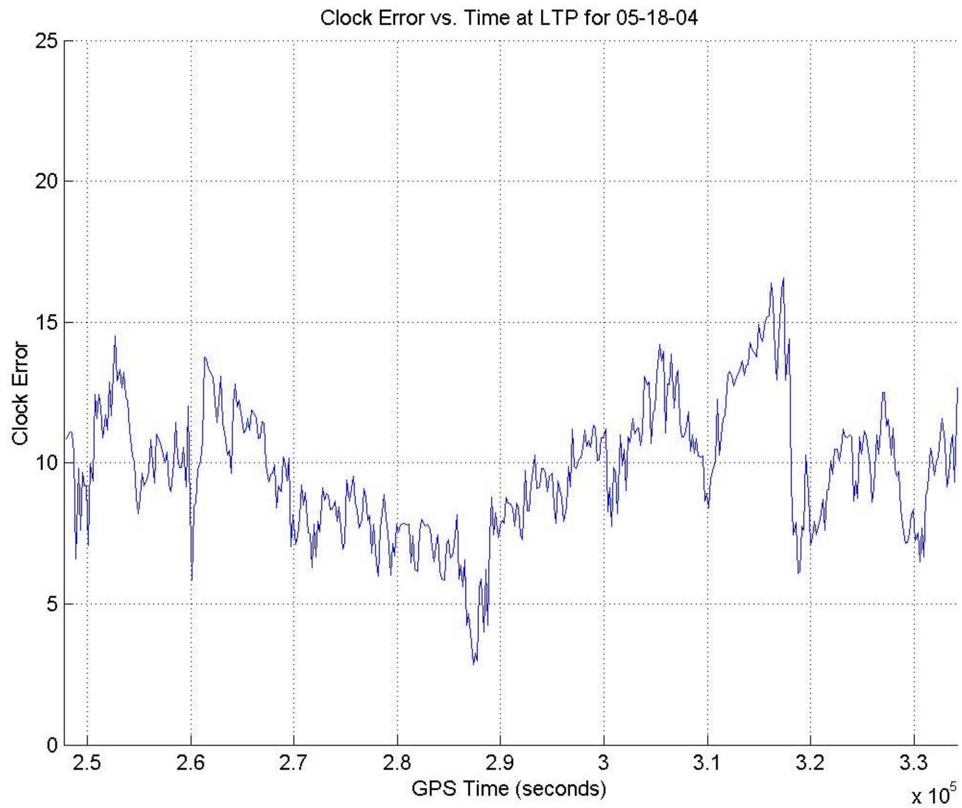
8.4.3.3 May VDOP and # of SV Observations versus Time



8.4.3.4 May HDOP and # of SV Observations versus Time

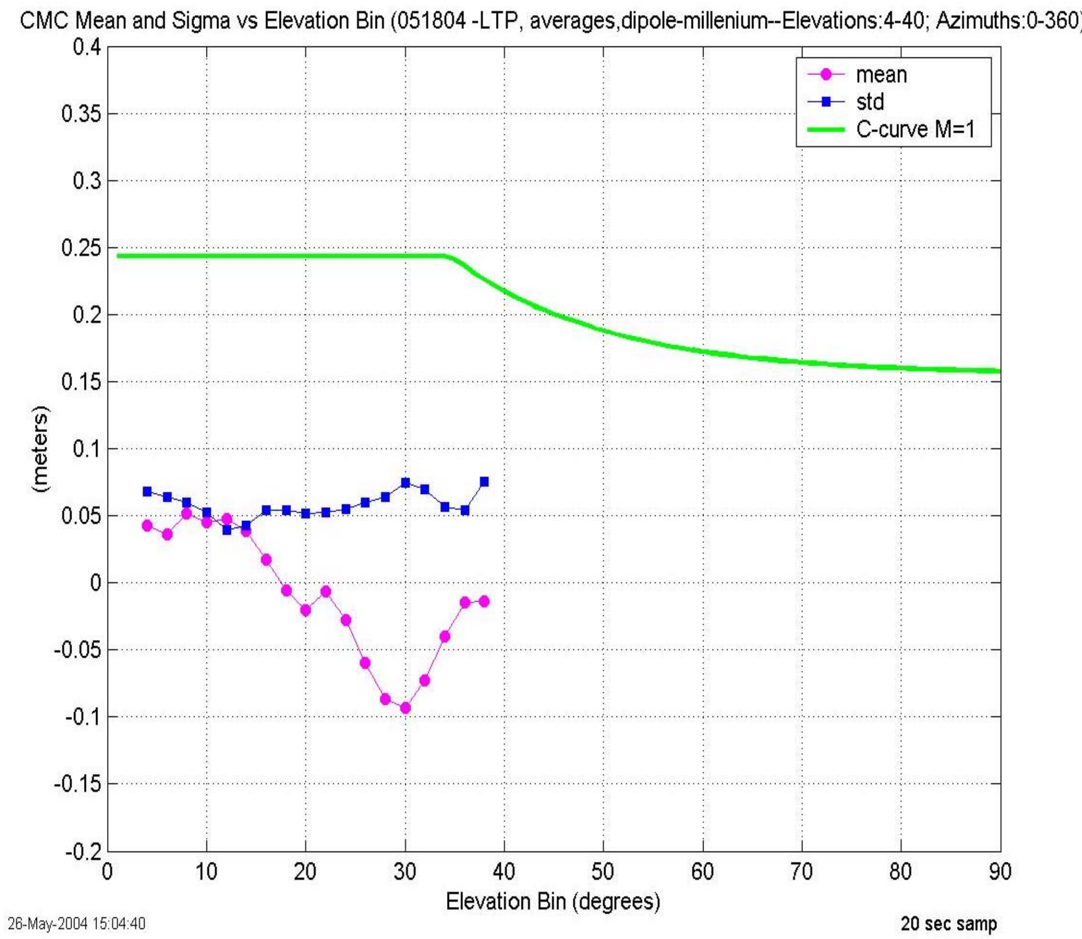


8.4.3.5 May Clock Error versus Time

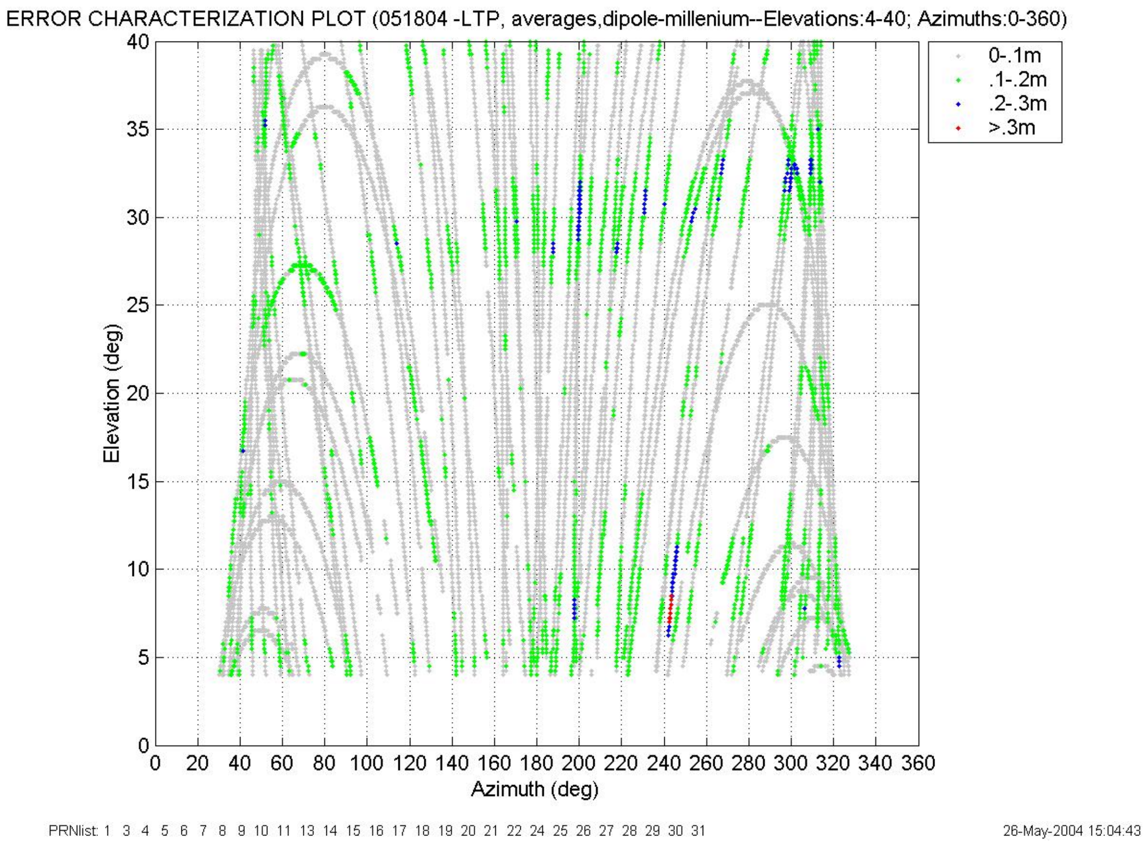


8.4.3.6 May Dipole Status and CMC (System Average) (multiple)

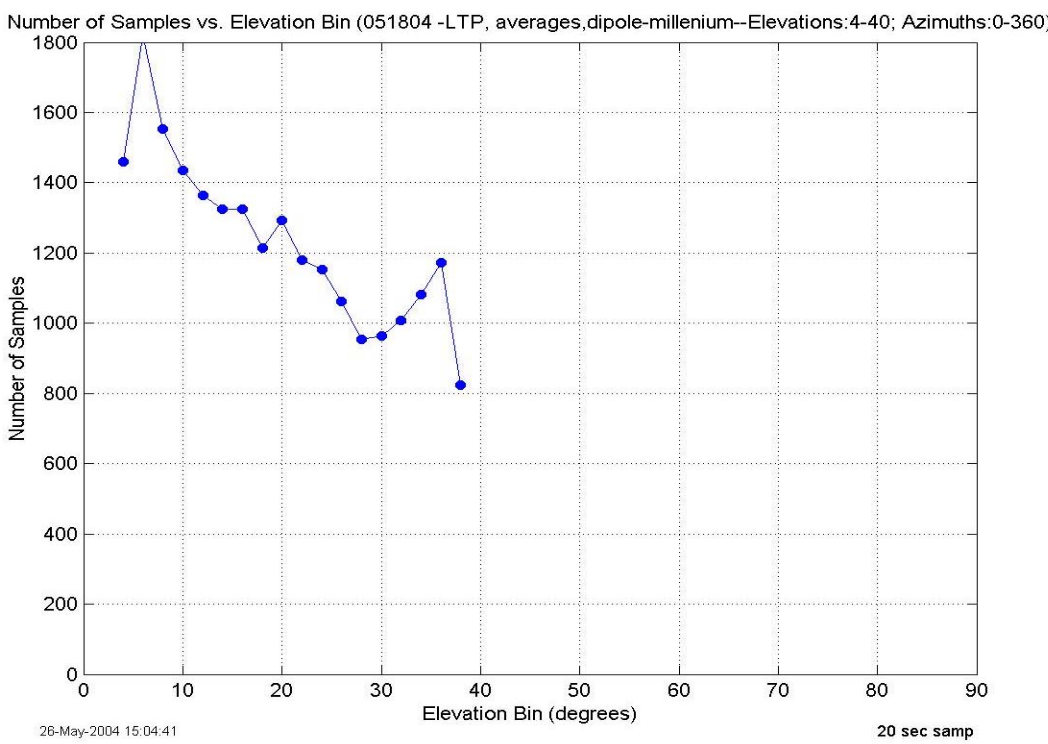
8.4.3.6.1 May System Dipole CMC Standard Deviation and Mean versus Elevation



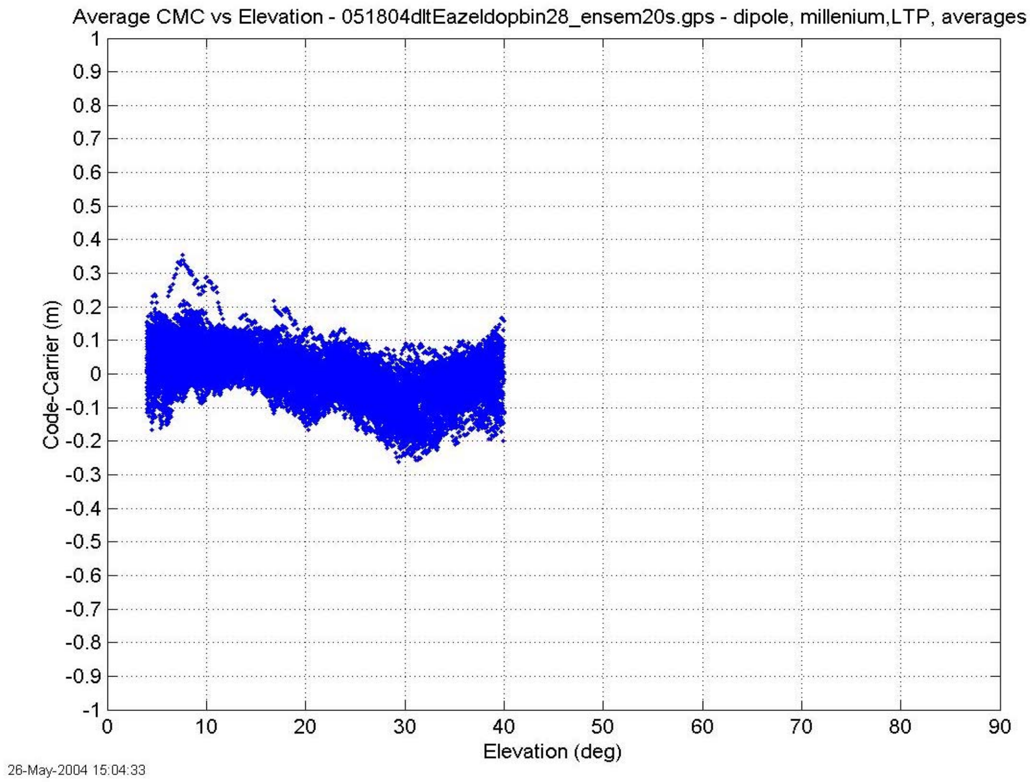
8.4.3.6.2 May System Dipole Error Characterization versus Azimuth and Elevation



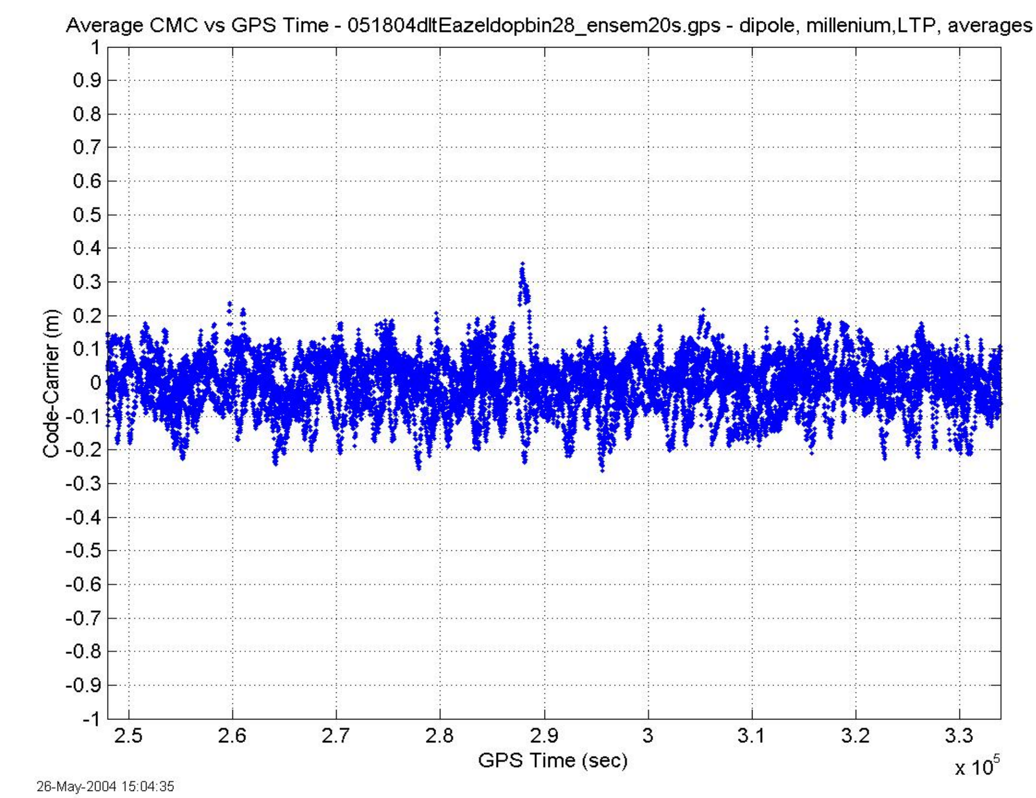
8.4.3.6.3 May System Dipole Number of Sample versus Elevation



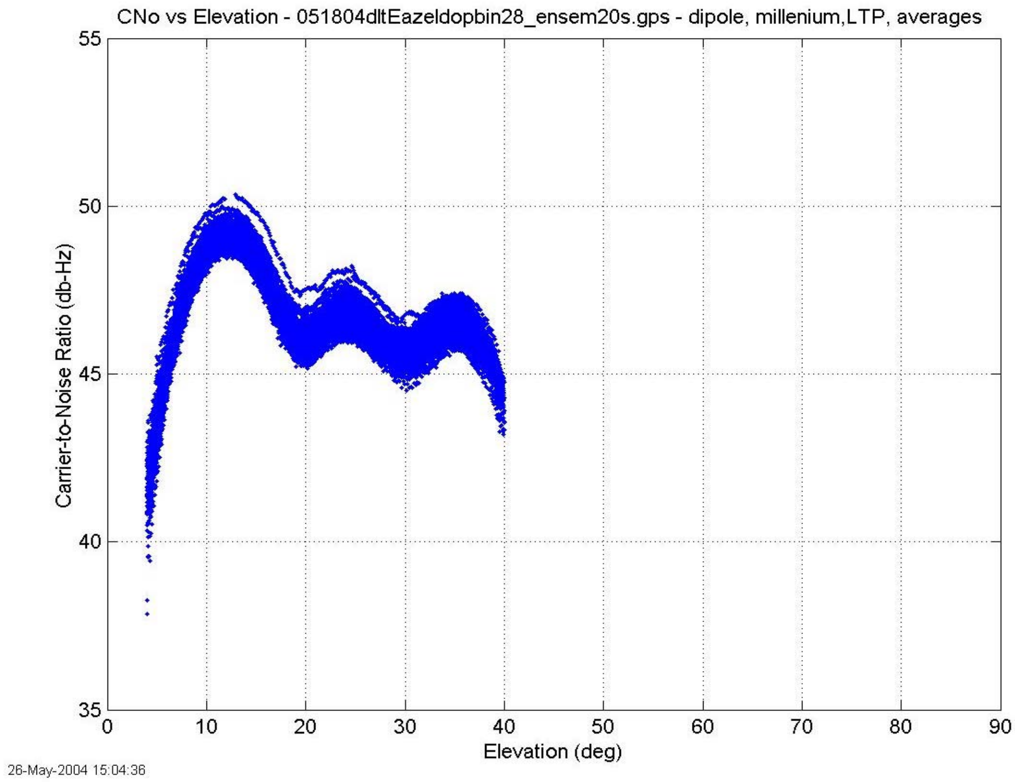
8.4.3.6.4 May System Dipole CMC versus Elevation



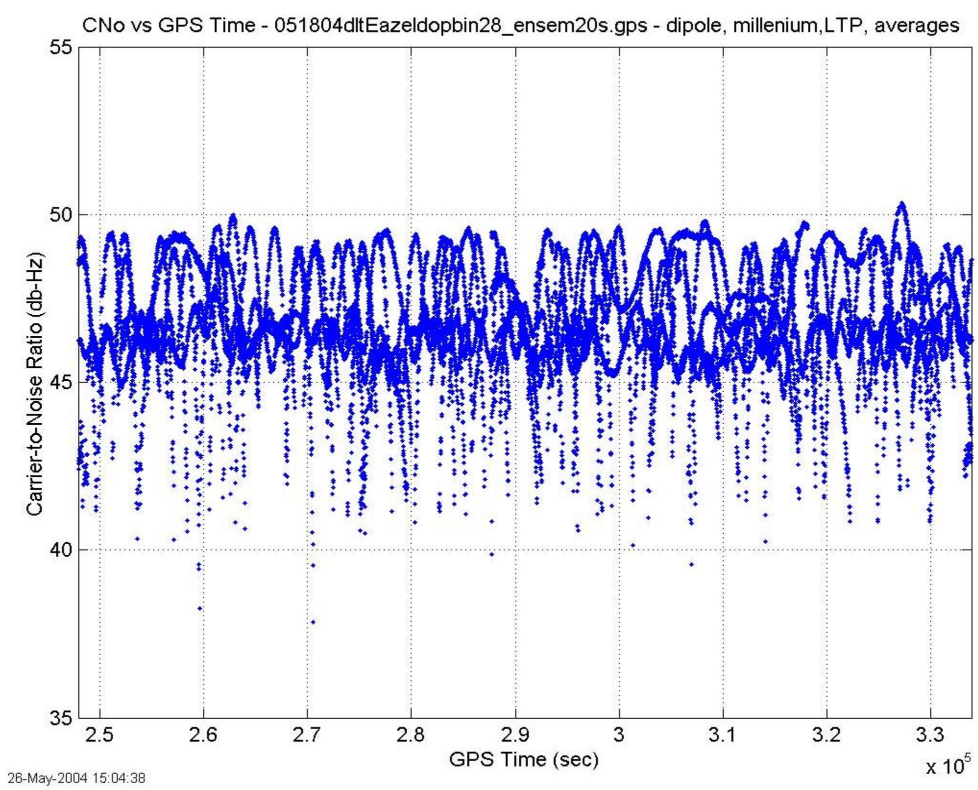
8.4.3.6.5 May System Dipole CMC versus Time



8.4.3.6.6 May System Dipole Carrier to Noise versus Elevation

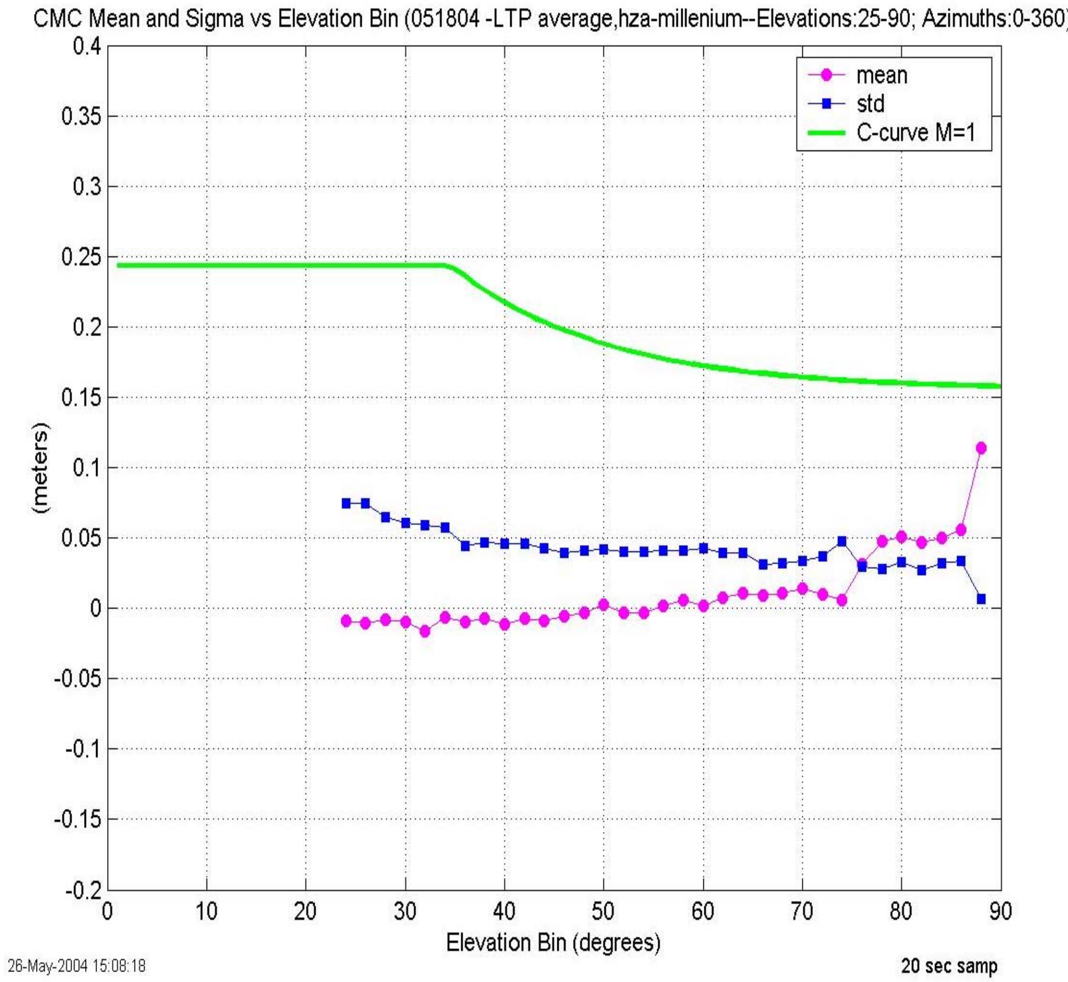


8.4.3.6.7 May System Dipole Carrier to Noise versus Time

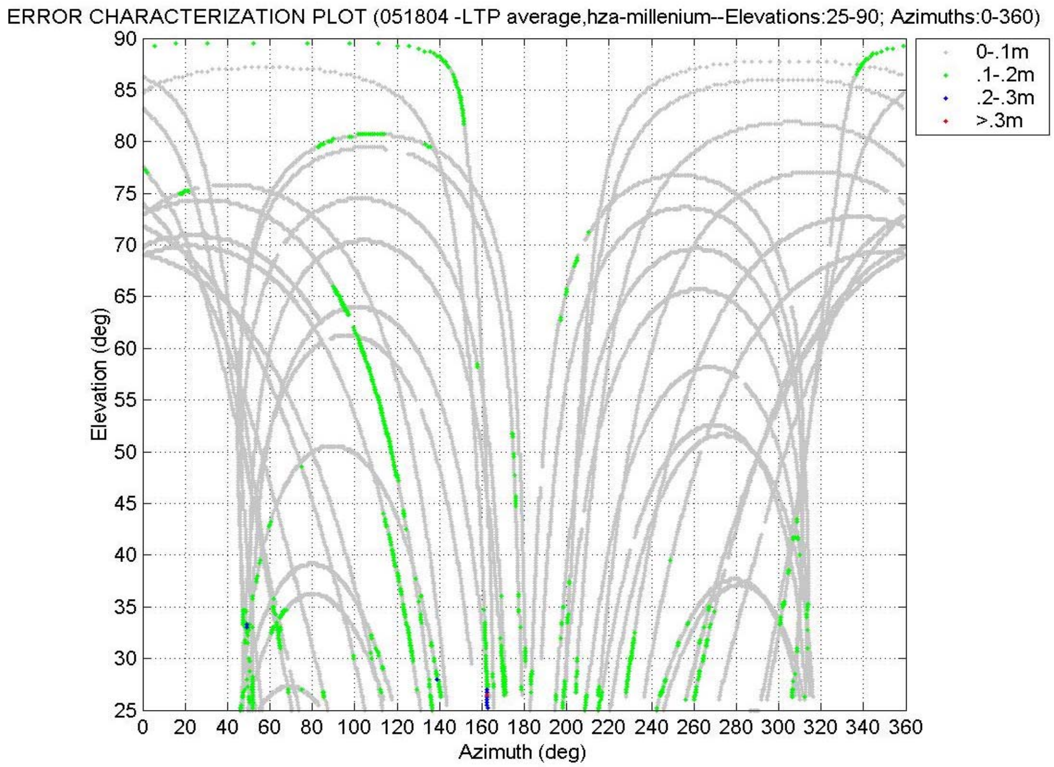


8.4.3.7 May HZA Status and CMC (System Average) (multiple)

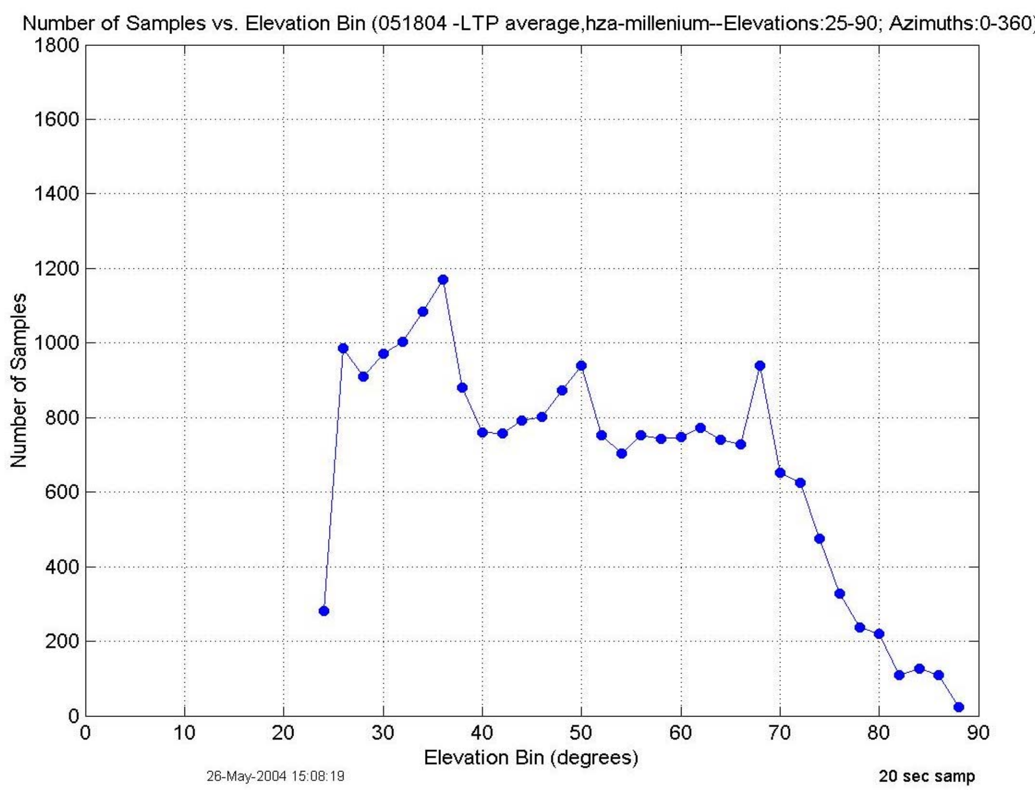
8.4.3.7.1 May System HZA CMC Standard Deviation and Mean versus Elevation



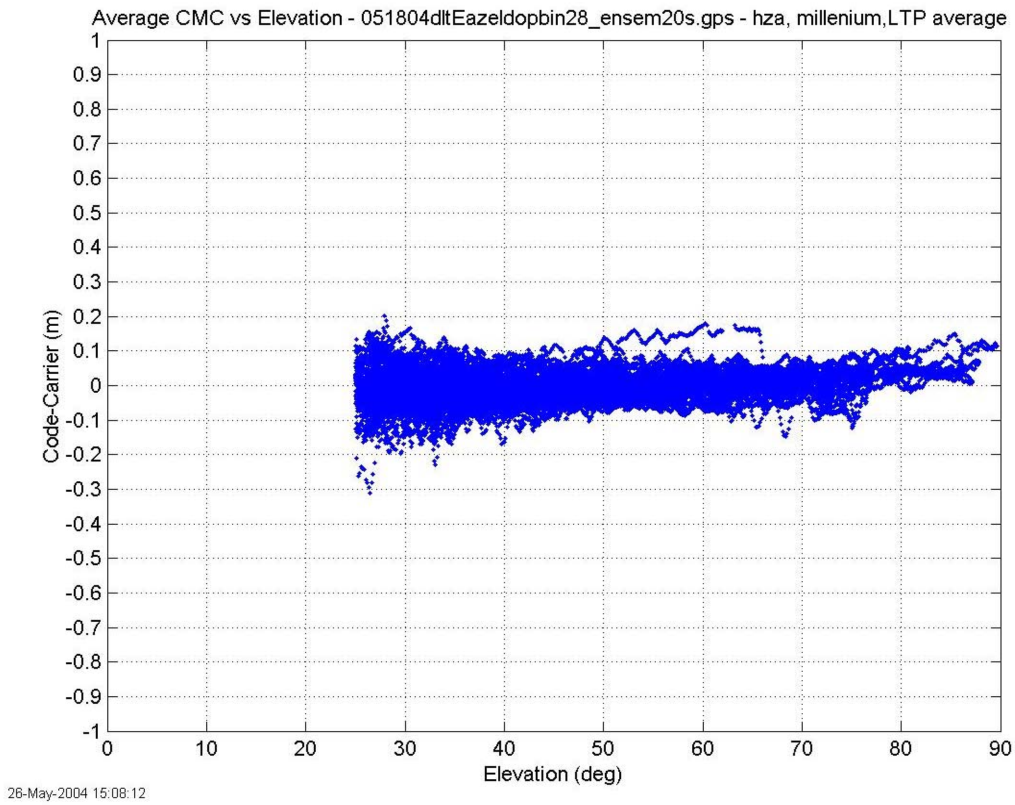
8.4.3.7.2 May System HZA Error Characterization versus Azimuth and Elevation



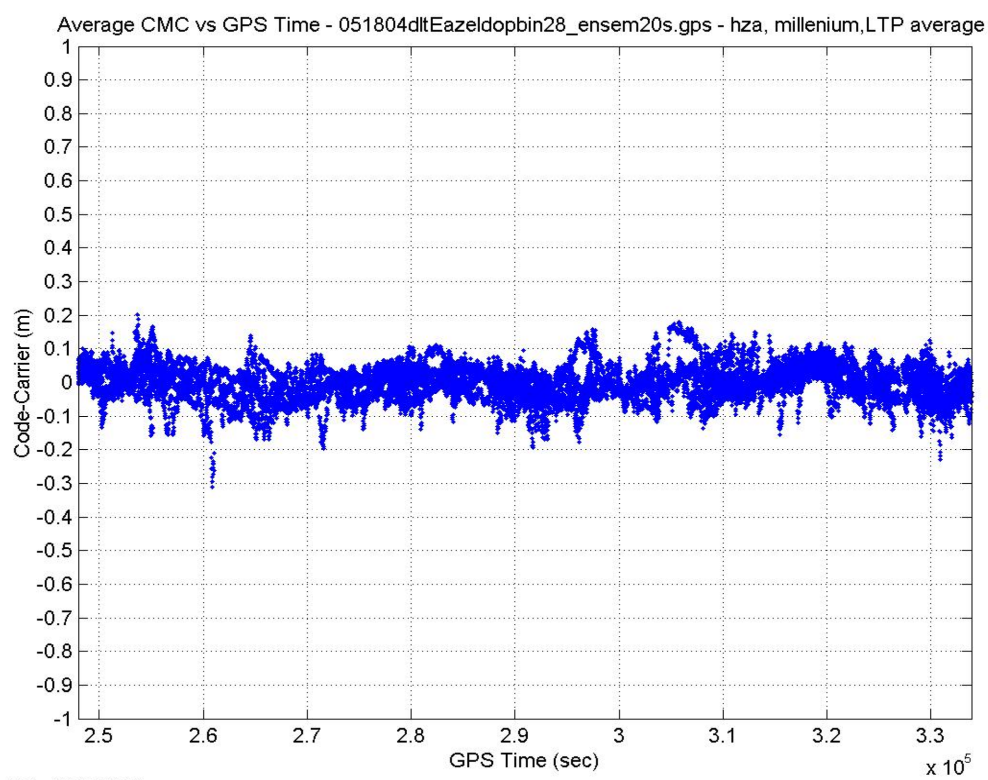
8.4.3.7.3 May System HZA Number of Sample versus Elevation



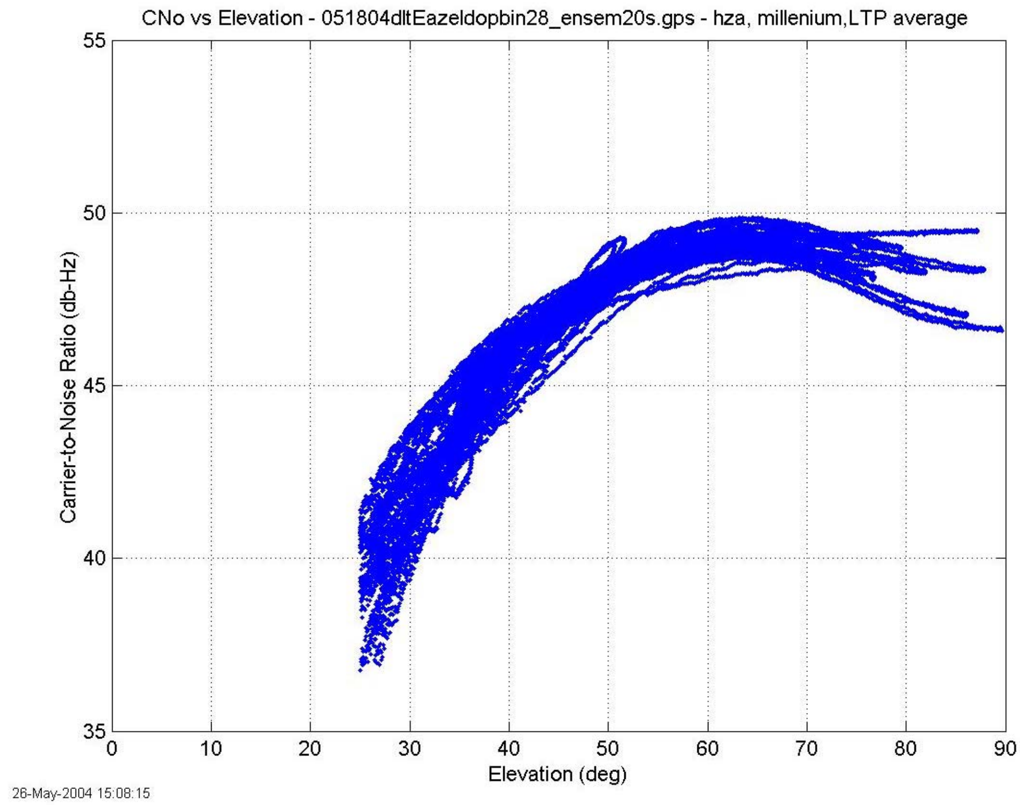
8.4.3.7.4 May System HZA CMC versus Elevation



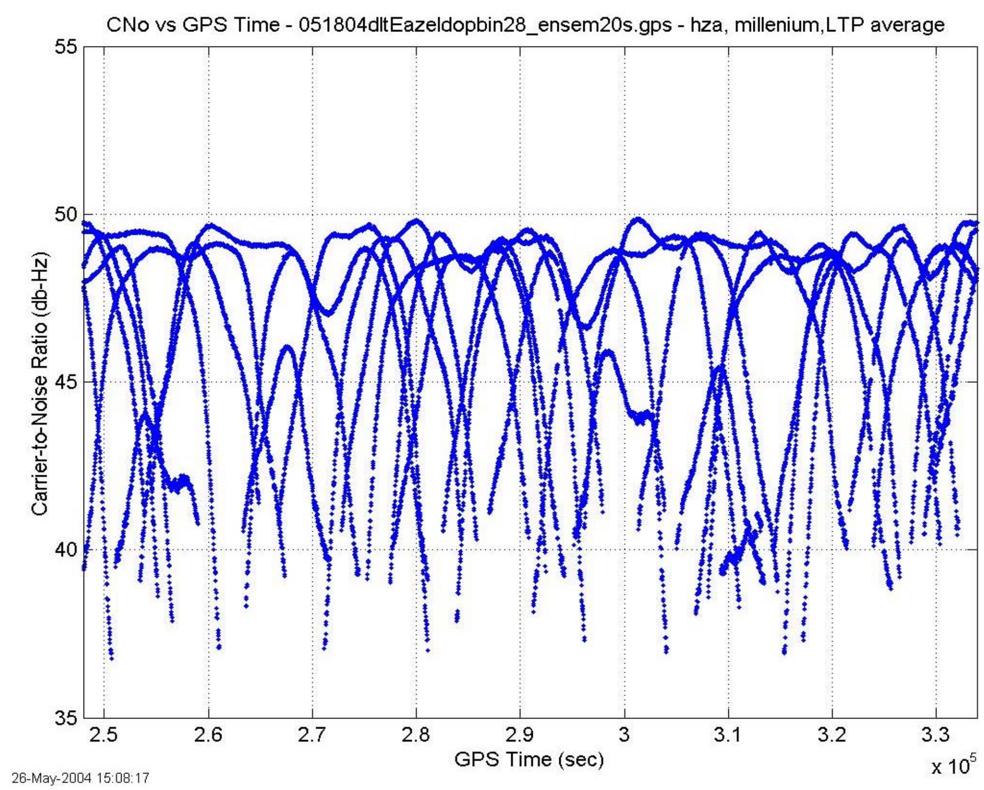
8.4.3.7.5 System HZA CMC versus Time



8.4.3.7.6 May System HZA Carrier to Noise versus Elevation

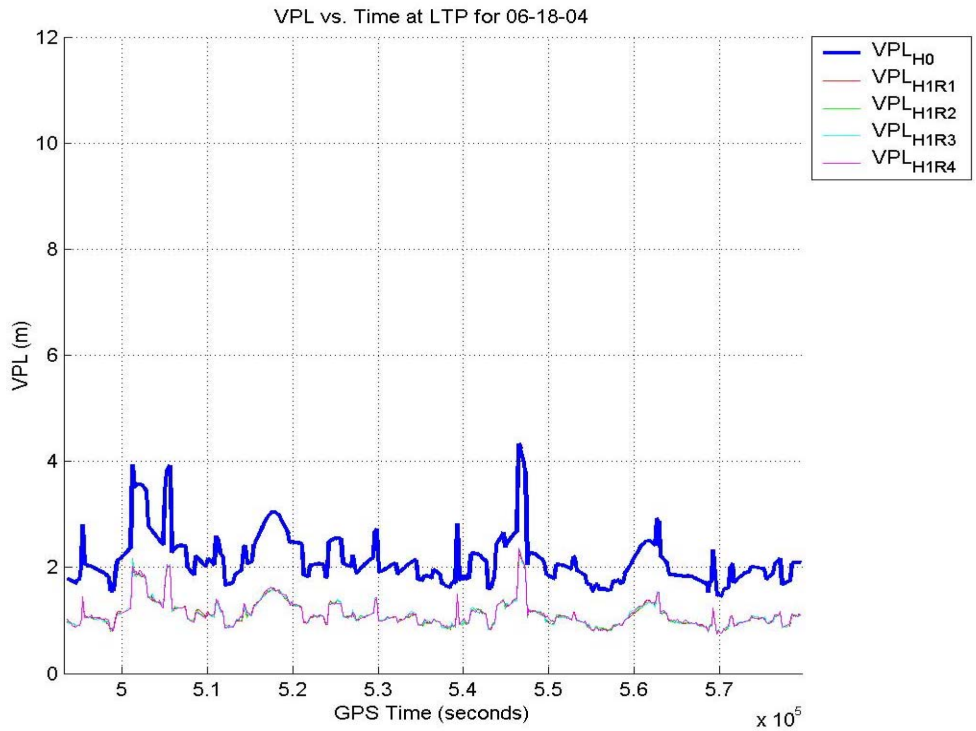


8.4.3.7.7 May System HZA Carrier to Noise versus Time

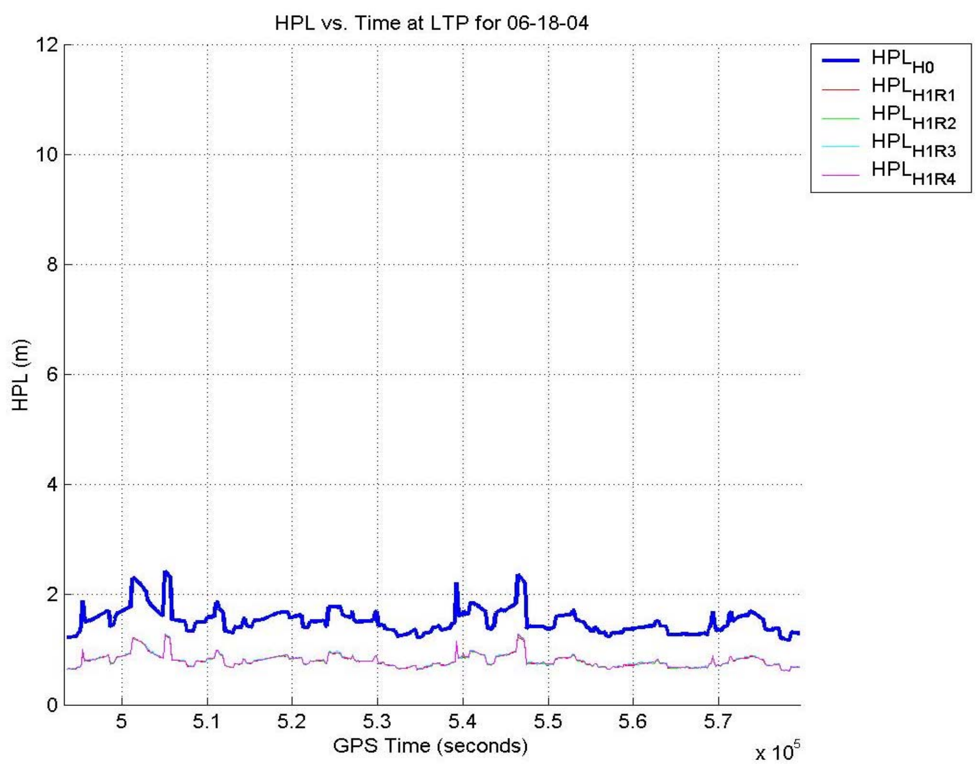


8.4.4 June 2004 Performance Plots

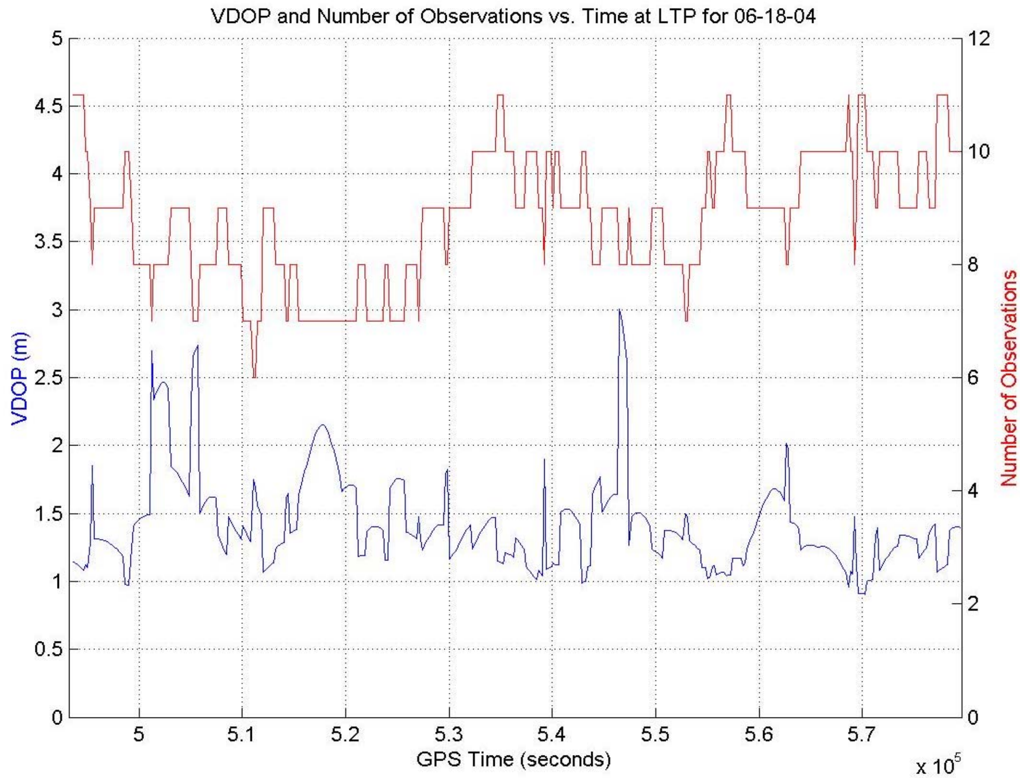
8.4.4.1 June VPL versus Time



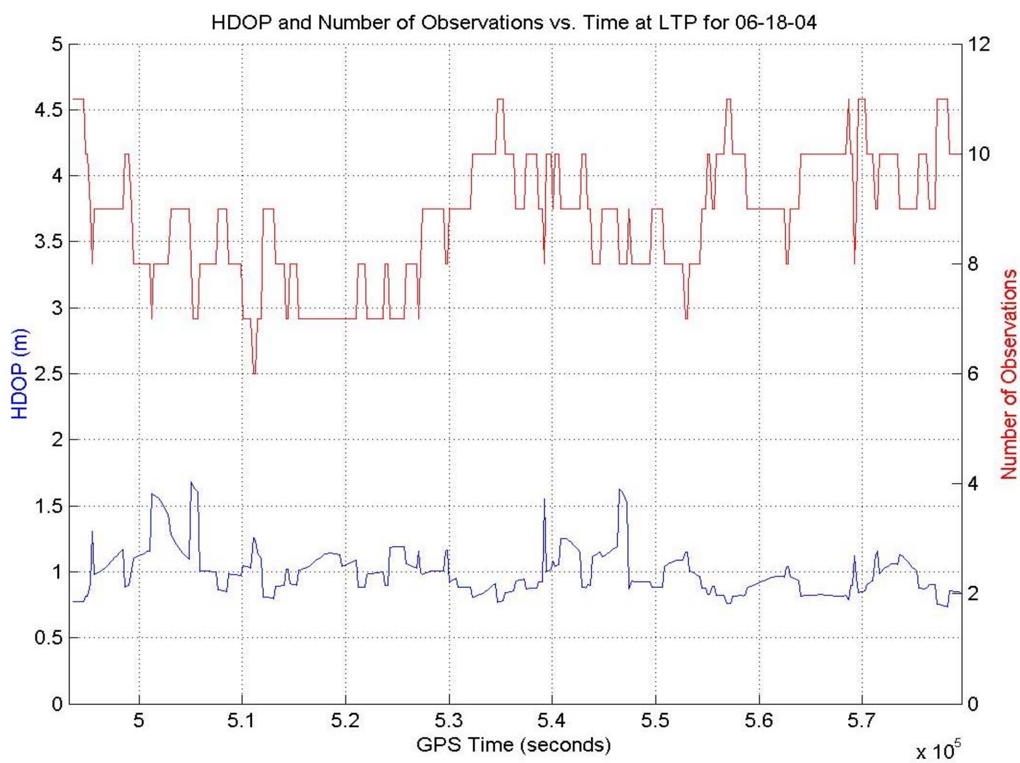
8.4.4.2 June HPL versus Time



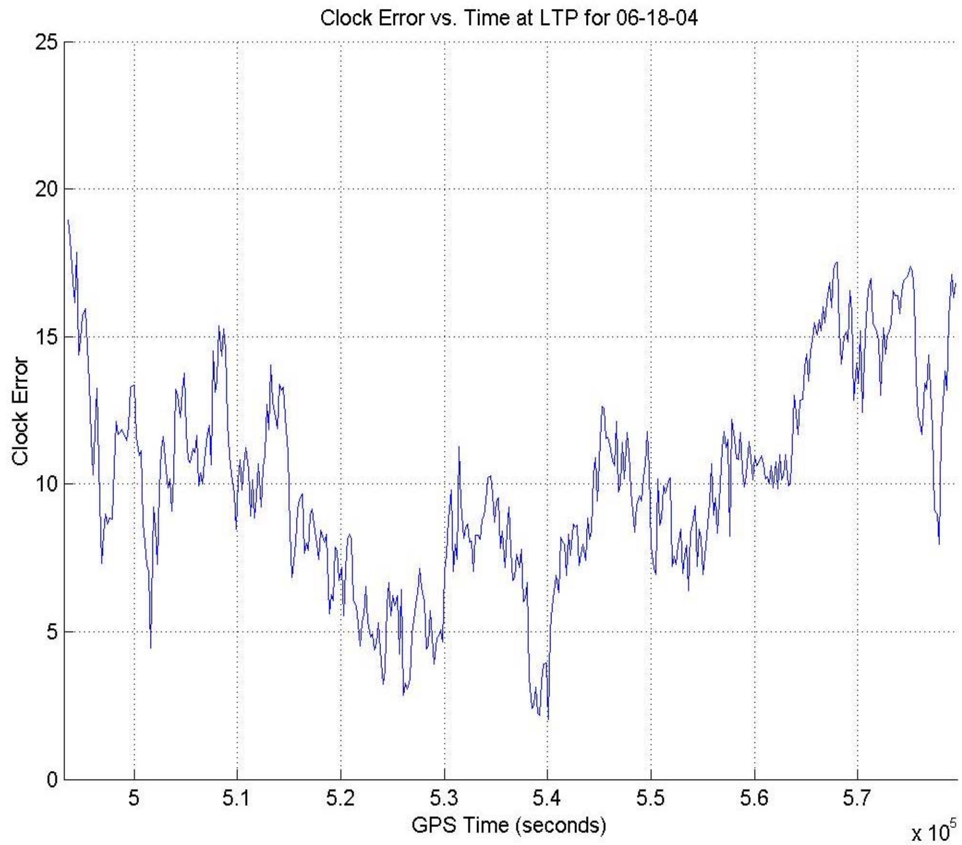
8.4.4.3 June VDOP and # of SV Observations versus Time



8.4.4.4 June HDOP and # of SV Observations versus Time

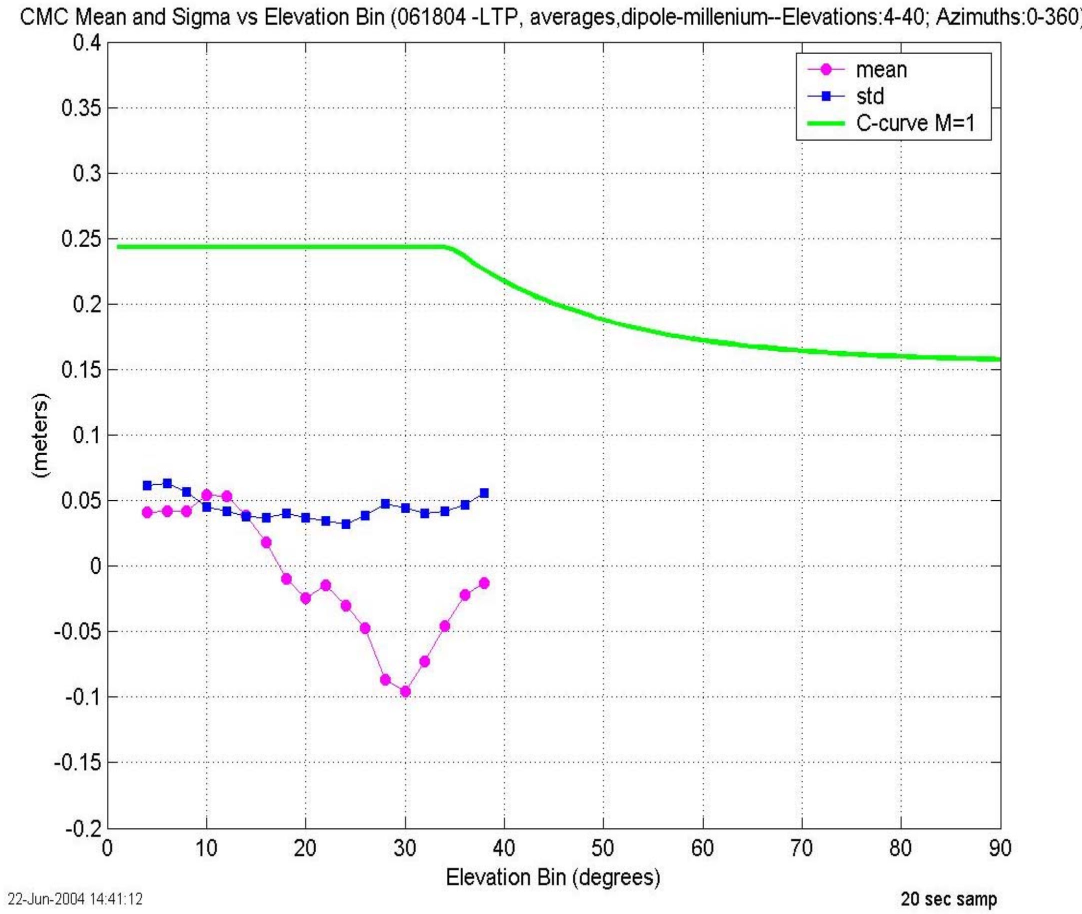


8.4.4.5 June Clock Error versus Time

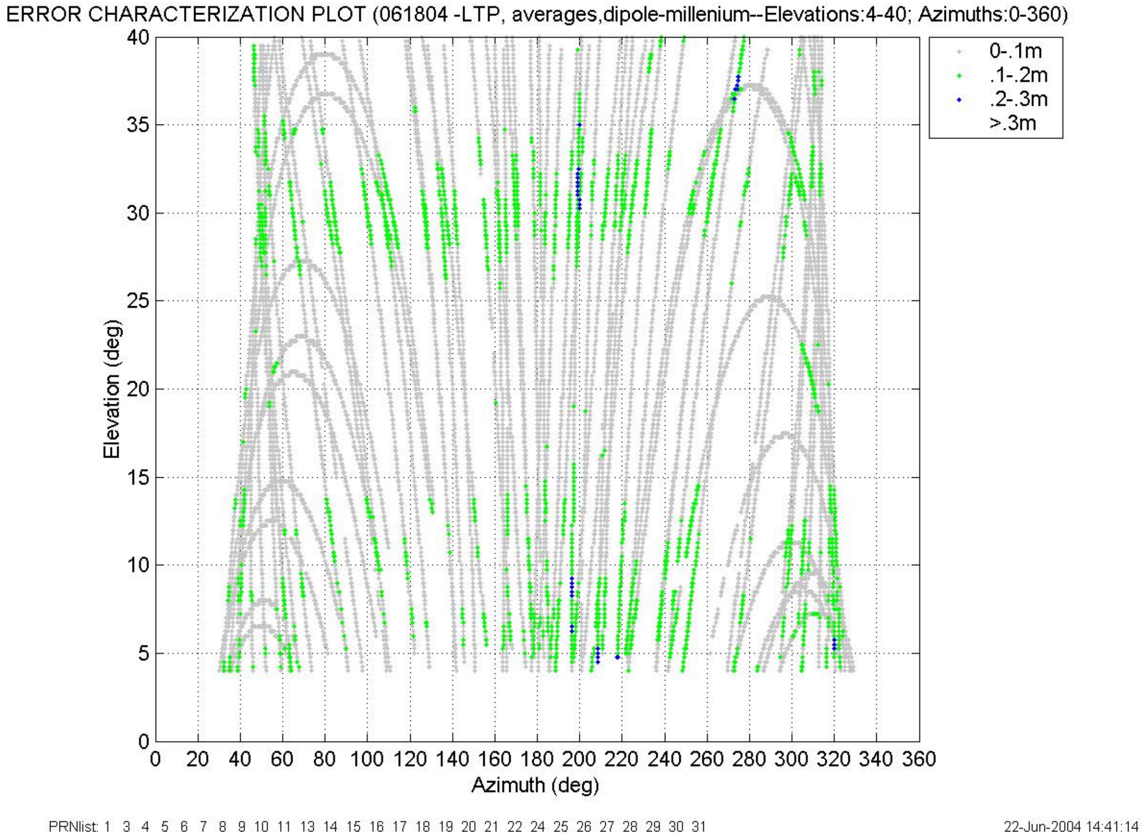


8.4.4.6 June Dipole Status and CMC (System Average) (multiple)

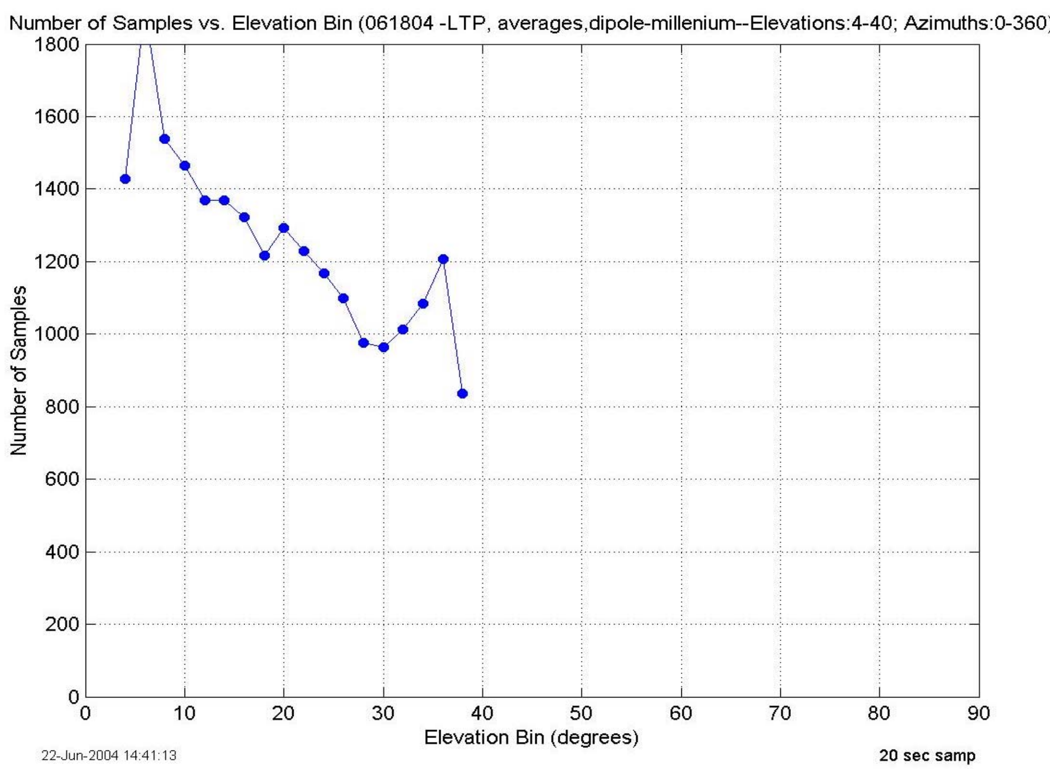
8.4.4.6.1 June System Dipole CMC Standard Deviation and Mean versus Elevation



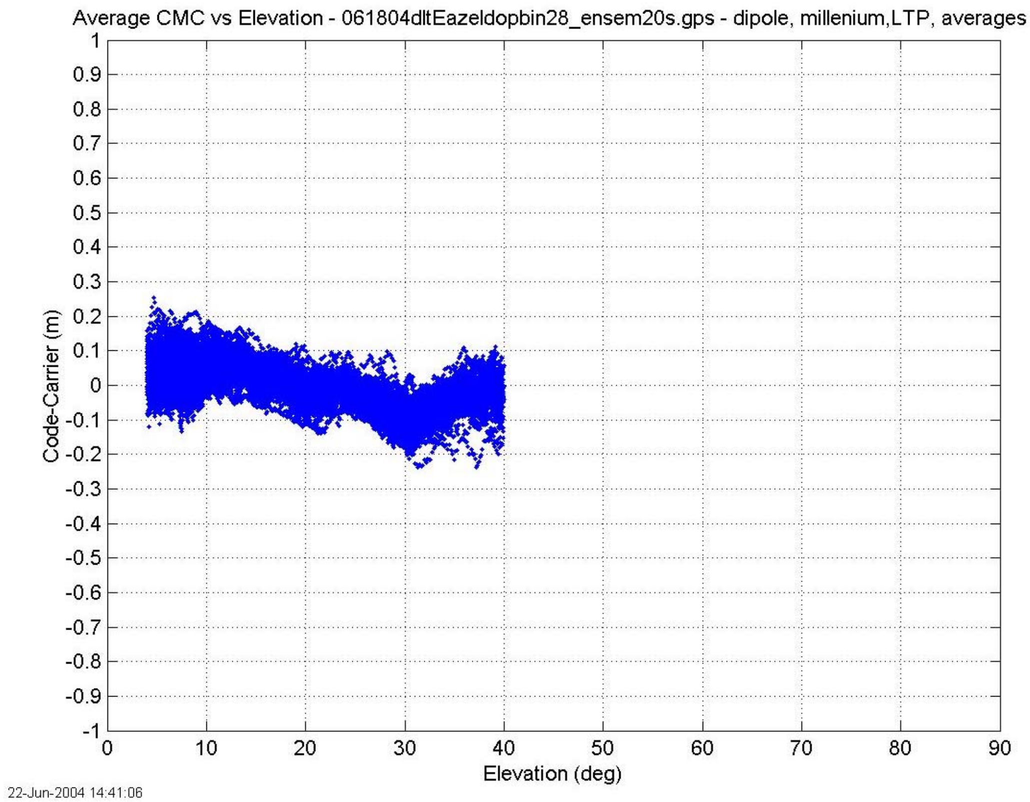
8.4.4.6.2 June System Dipole Error Characterization versus Azimuth and Elevation



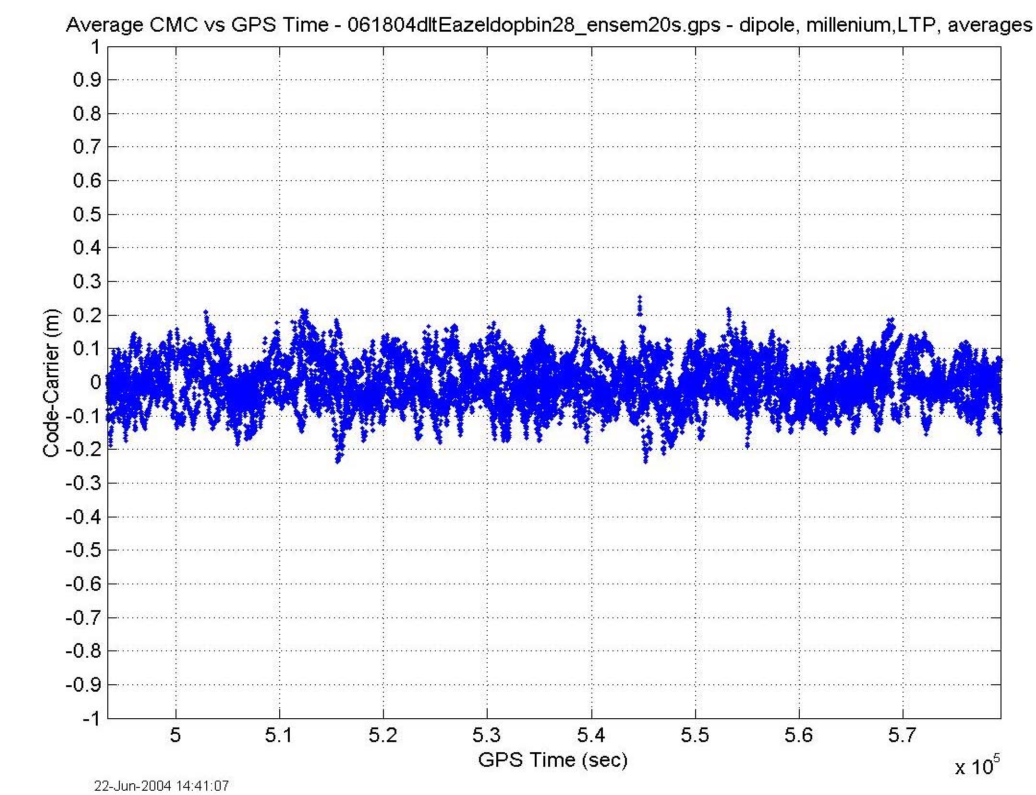
8.4.4.6.3 June System Dipole Number of Sample versus Elevation



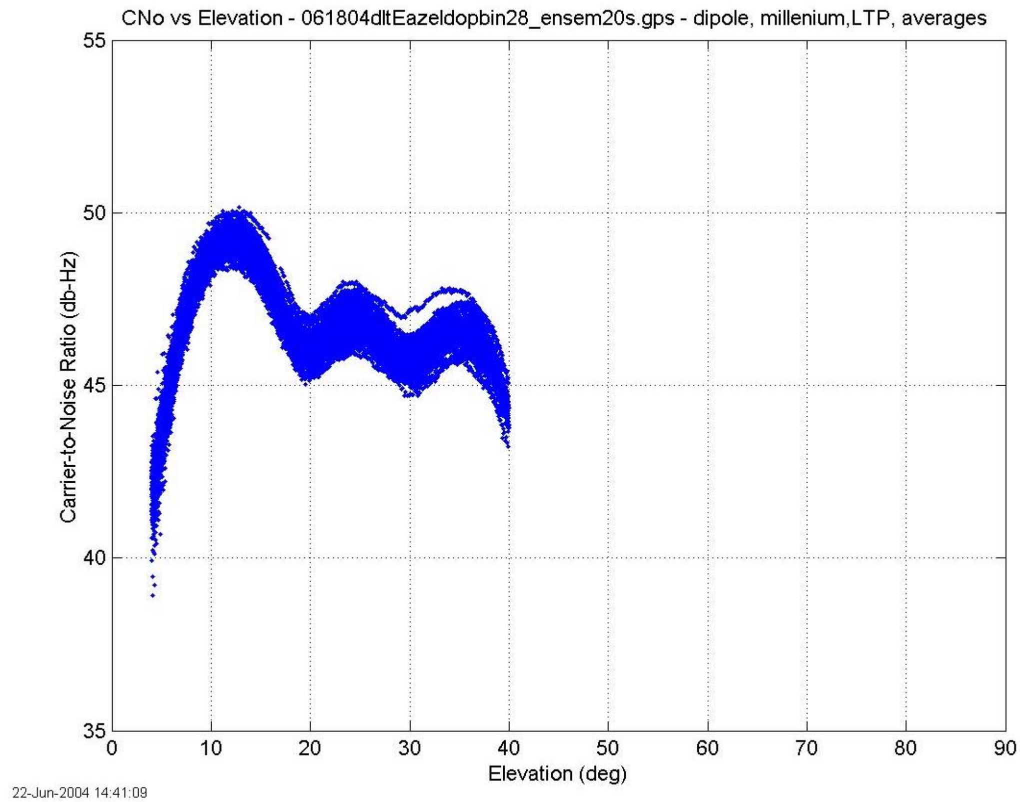
8.4.4.6.4 June System Dipole CMC versus Elevation



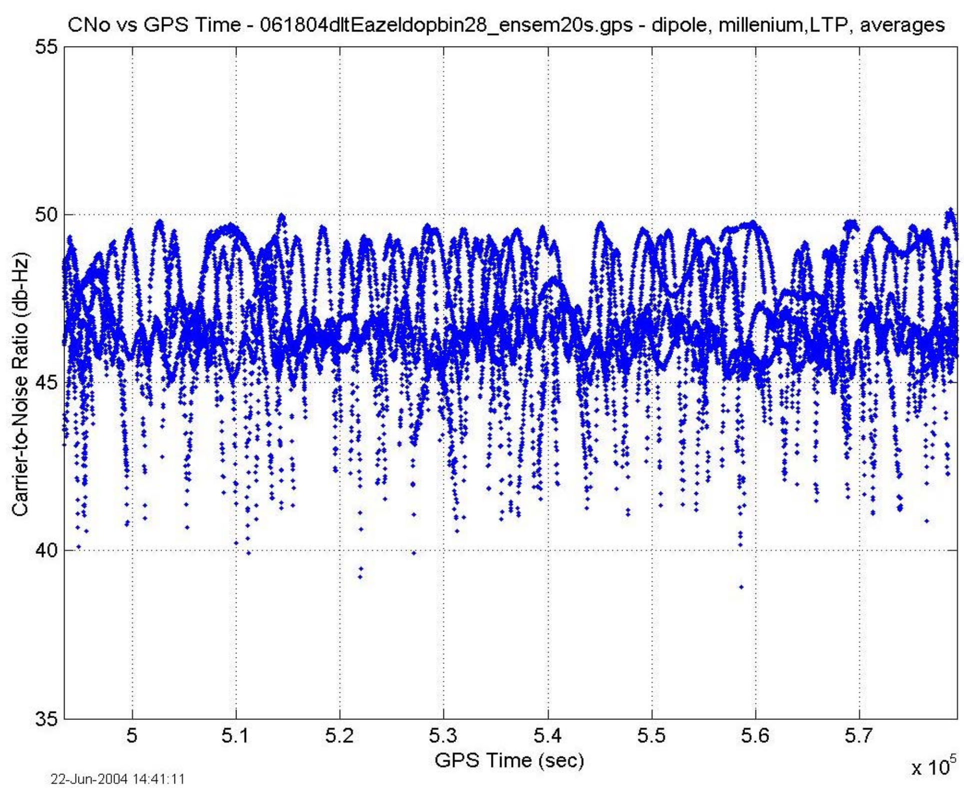
8.4.4.6.5 June System Dipole CMC versus Time



8.4.4.6.6 June System Dipole Carrier to Noise versus Elevation

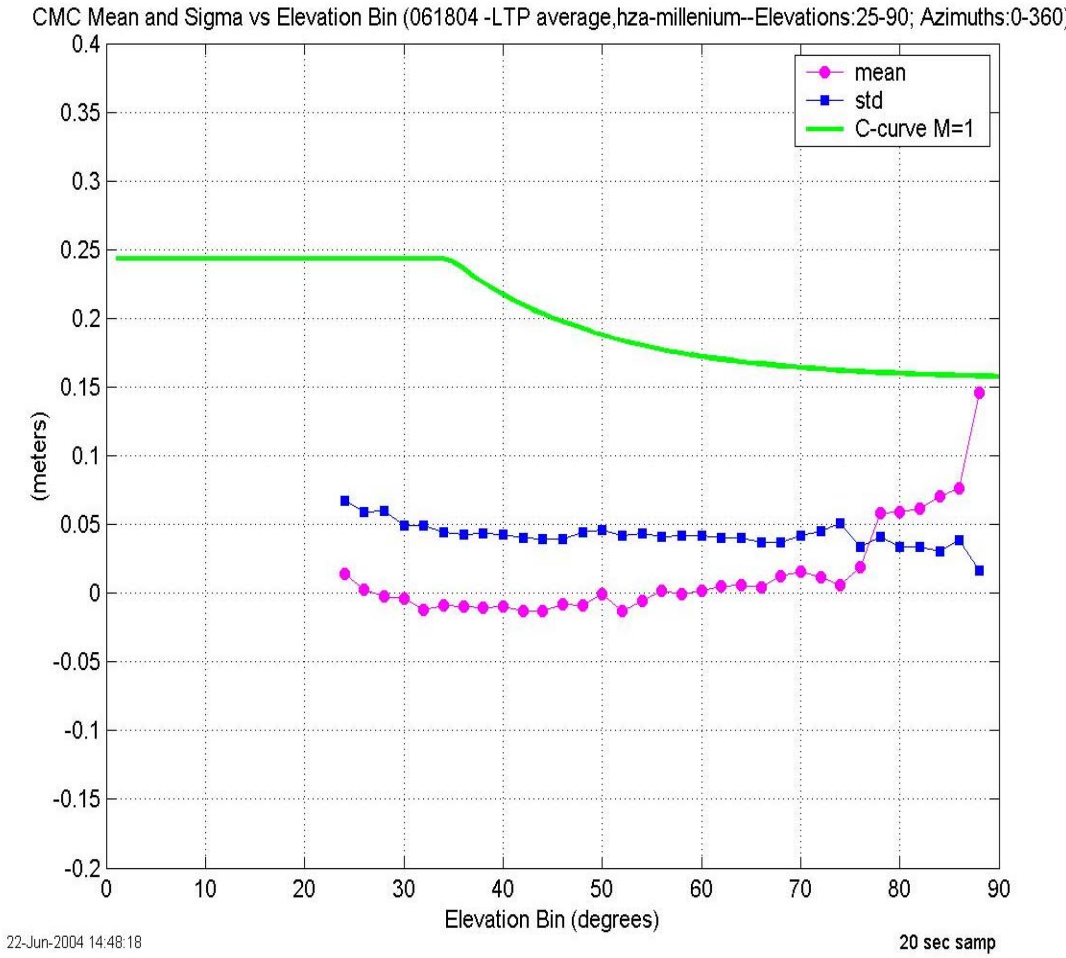


8.4.4.6.7 June System Carrier to Noise versus Time

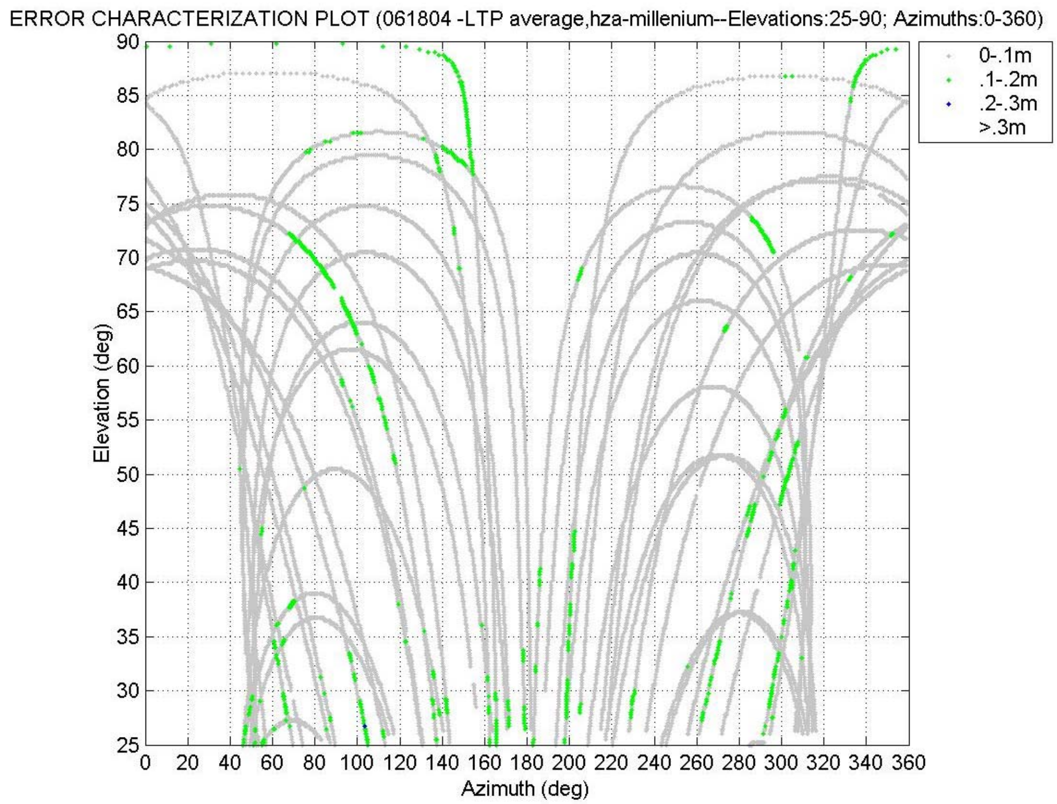


8.4.4.7 June HZA Status and CMC (System Average) (multiple)

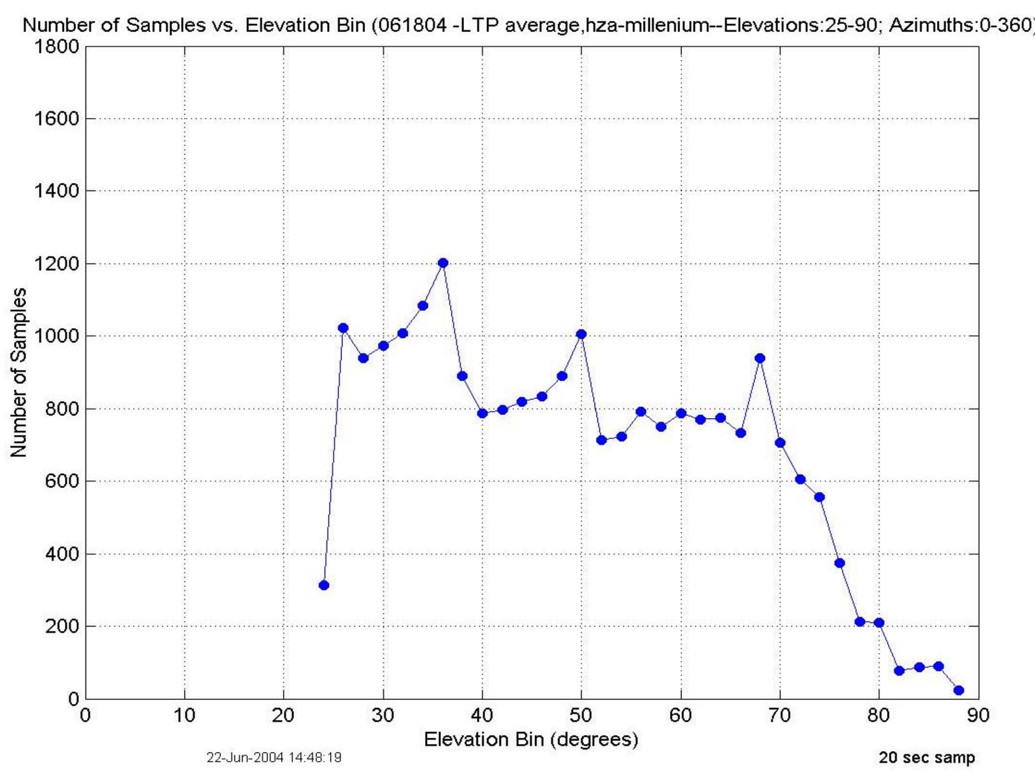
8.4.4.7.1 June System HZA CMC Standard Deviation and Mean versus Elevation



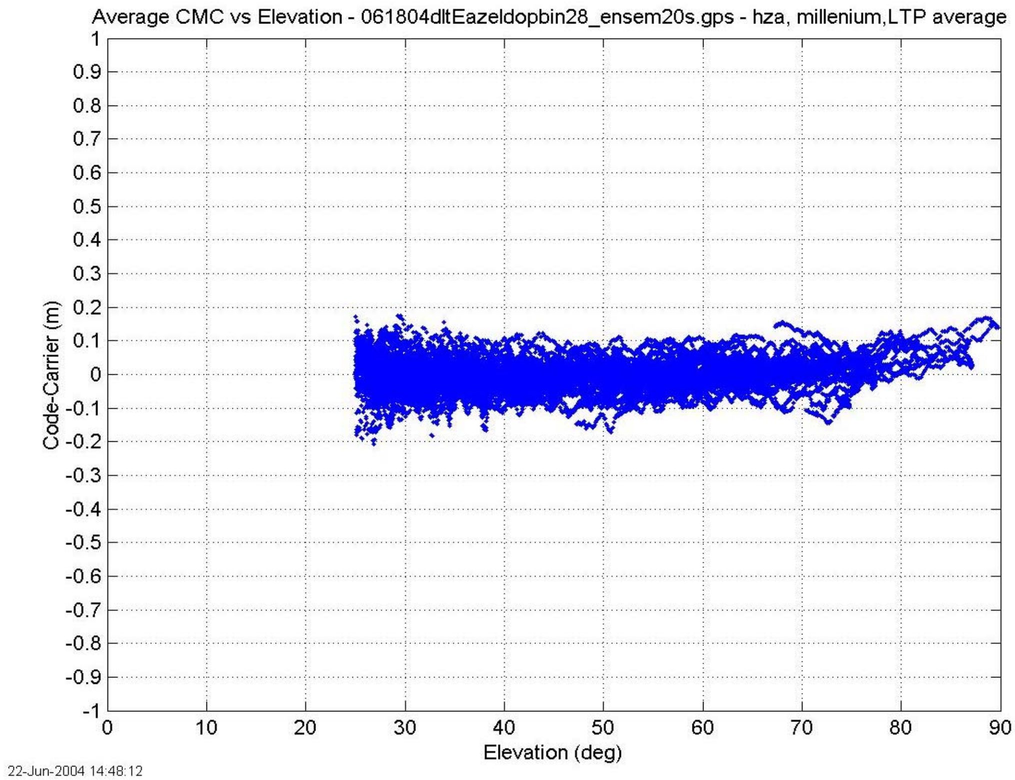
8.4.4.7.2 June System HZA Error Characterization versus Azimuth and Elevation



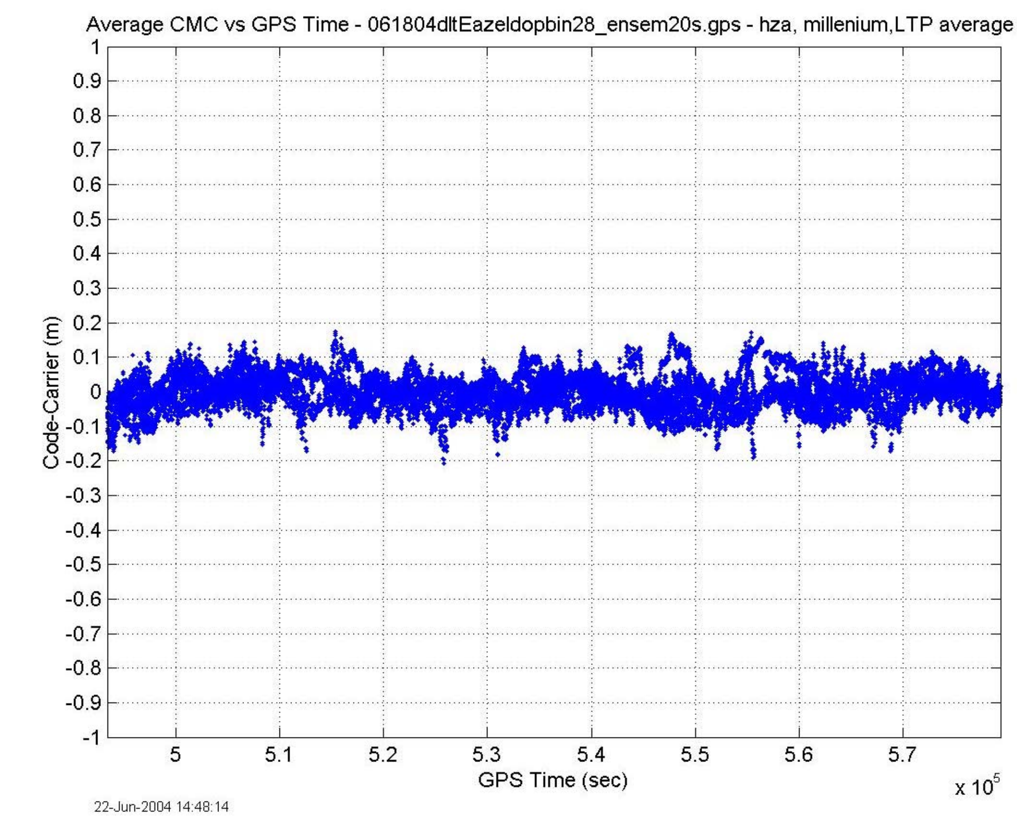
8.4.4.7.3 June System HZA Number of Sample versus Elevation



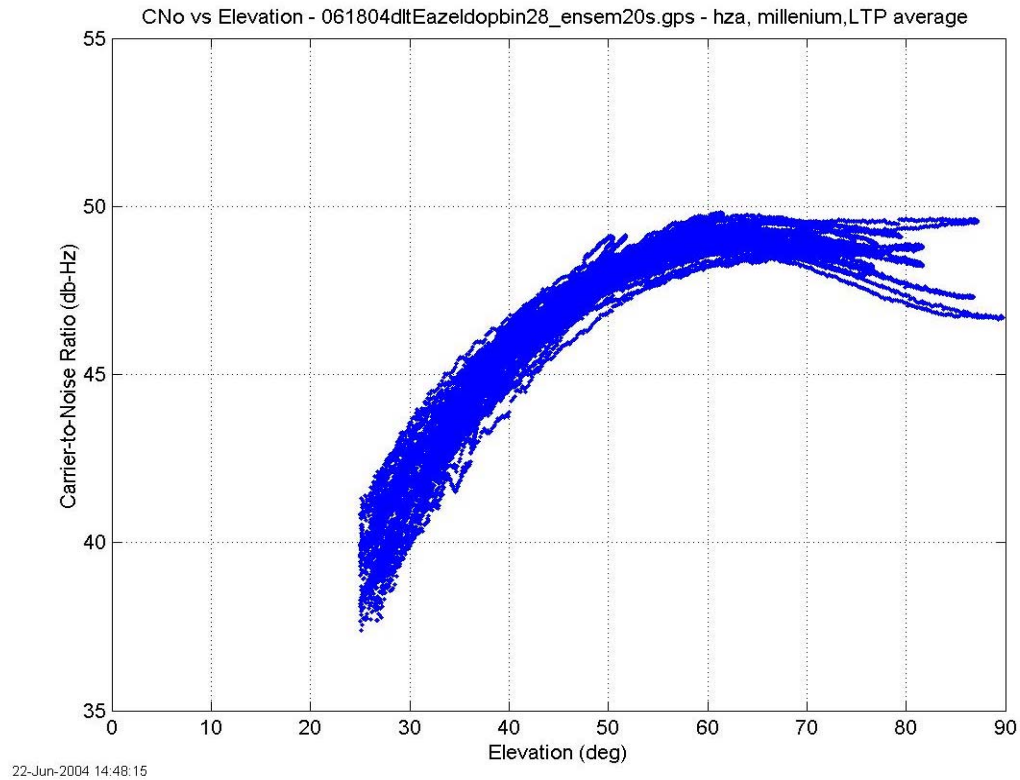
8.4.4.7.4 June System HZA CMC versus Elevation



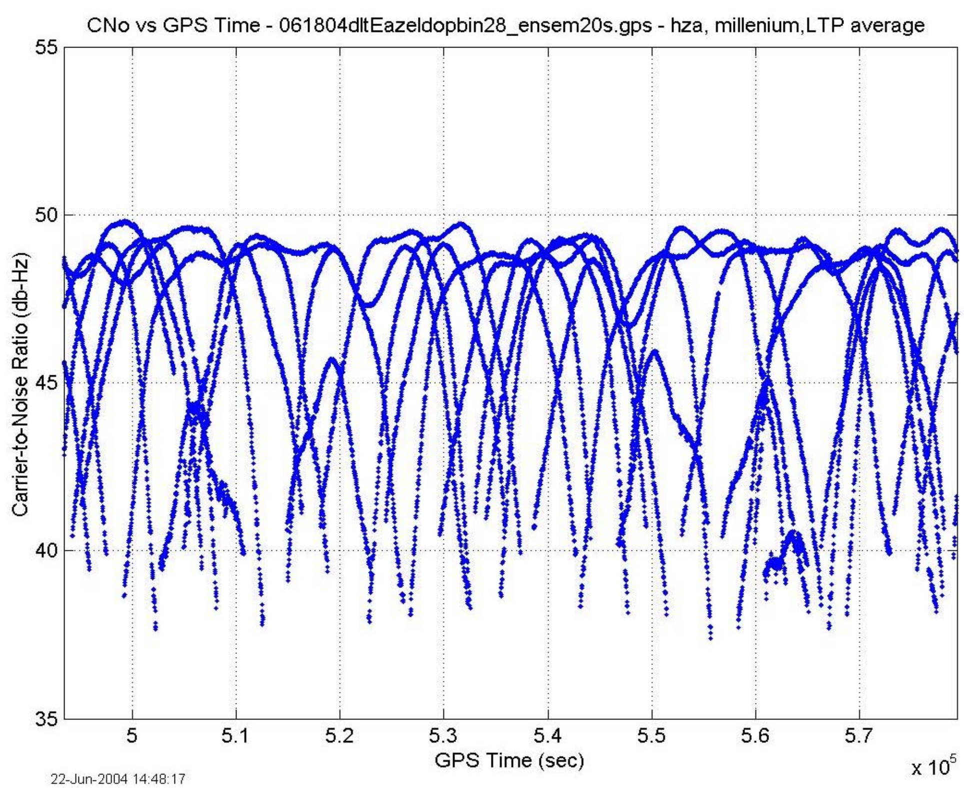
8.4.4.7.5 June System HZA CMC versus Time



8.4.4.7.6 June System HZA Carrier to Noise versus Elevation



8.4.4.7.7 June System HZA Carrier to Noise versus Time



9. Glossary of Terms and Acronyms

A

ACY
Atlantic City International Airport i
AGC
Automatic Gain Control 14
AOA
Air Operations Area i

B

B-value
An estimation of the pseudorange correction error 18

C

C/No
Carrier-to-noise 14
Cat
Category 12
CDI
Course Deviation Indicator 10
CMC
Code Minus Carrier 1
CPU
Central Processing Unit 7

E

EOW
End Of Week 14

F

FAA
Federal Aviation Administration i
FC
Flight Change 10

G

H

I

L

M

N

O

P

R

W

10. Index of Tables and Figures

10.1 Tables

10.2 Figures